European Commission

EU-level technical guidance on adapting buildings to climate change

BEST PRACTICE GUIDANCE

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European Commission

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Abbreviations and acronyms

The following abbreviations and acronyms are used within this guide.

AHU	Air-handing unit
AU	Austria
BE	Belgium
BREEAM	Building Research Establishment Environmental Assessment Method (Certification)
CCTV	Closed-circuit television
CVRA	Climate Vulnerability and Risk Assessment
DK	Denmark
EU	European Union
FEMA	Federal Emergency Management Agency
HVAC	Heating, ventilation, and air conditioning
LEED	Leadership in Energy and Environmental Design (Certification)
NL	Netherlands
NO	Norway
PL	Poland
PV	Photo voltaic
SuDs	Sustainable urban drainage system
UK	United Kingdom
UNEP	United Nations Environment Programme
UV	Ultraviolet

Table of Contents

Introduction

Climate forms a key consideration in the design, construction and operation of buildings. Climate change is already causing observable effects on the environment and impacting the buildings in which we live and work. Some of these observable effects include more extreme temperatures, higher wind speeds and heavier precipitation, all of which negatively impact buildings and their users.

This document aims to:

- Provide **technical guidance** on **climate-adaptation measures** at the building scale. These adaptation measures aim to be relevant for both **new** and **existing buildings**, across the different climatic zones of Europe.
- Present adaptation solutions that **reduce** the **most important** identified **climate risks** that affect the **built environment** (as categorised by the EU Taxonomy).
- **Orientate stakeholders** across the building industry to the **actions** they can take to improve building performance. This includes strategies for owners, operators, users, policy makers, engineers, architects and insurers.
- Support the development and alignment of **key EU policies.**

It is important to note that this document aims to provide a general overview of climate adaptation measures, for a wide variety of building types.

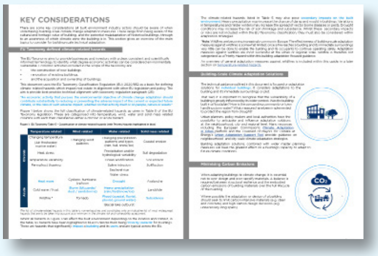
For detailed strategies, tailored to particular building types or environmental locations, appropriate professional guidance should be sought to ensure adaptations are effective against climate change.

Overview

This document is structured into three main sections.

Key considerations

There are a number of issues to be considered prior to identifying building-scale climate adaptations:



- EU Taxonomy climate-related hazards
- Building-scale adaptation solutions
- Minimising carbon emissions
- Climate vulnerability & risk assessments
- Future climate impacts
- Climate adaptation strategies and historic buildings

Best practice guidance

Building-scale solutions that can adapt buildings to climate related risks identified in the EU Taxonomy are presented in Sections 1 to 10.

Adapting buildings to priority hazards

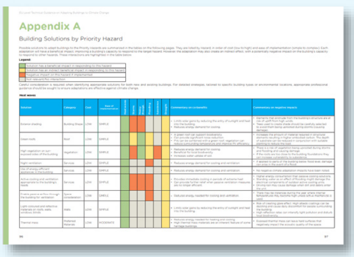
Technical guidance for adapting buildings to priority hazards is provided in Sections 1 to 6. Within this guide, a 'priority climate-related hazard' is defined as a hazard that significantly impacts a building and its users.

Adapting buildings to wider-climate related hazards

Technical guidance for adapting buildings to wider climate-related hazards is provided in Sections 7 to 10.

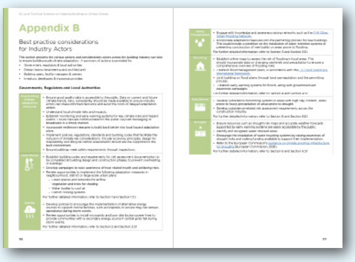
Quick reference summaries

The solutions detailed in this Best practice guidance are summarised in two quick reference guides.



Adaptation solutions for priority hazards

An overview of solutions is presented for each priority hazard. These are listed in order of **cost** (low to high) and **ease of implementation** (simple to complex).



Adaptation solutions by industry actor

Throughout this guide, recommended actions and considerations are provided for actors across the built environment industry, from local authorities, investors, developers, engineers and architects to building users and owners. An overview of solutions is provided for each industry actor.

Key considerations

There are some key considerations all built environment industry actors should be aware of when undertaking building-scale climate change adaptation measures. These range from being aware of the cultural and heritage value of buildings and the potential maladaptation of historical buildings, through to an awareness of which climatic zone the building is in. This section gives an overview of the main topics to consider for building-scale technical adaptation.

EU Taxonomy defined climate-related hazards

The EU Taxonomy aims to provide businesses and investors with a clear, consistent and scientifically informed terminology to identify what degree of economic activities can be considered environmentally sustainable. Economic activities included in the scope of the taxonomy are:

- the construction of new buildings,
- the renovation of existing buildings,
- and the acquisition and ownership of buildings.

This document uses the EU Taxonomy Classification Regulation (EU) 2020/852 as a basis for defining climate-related hazards that impact real estate in alignment with other EU legislation and policy. The aim is to provide the best practice technical alignment with paragraph (25) of the Taxonomy Regulation:

'An economic activity that pursues the environmental objective of climate change adaptation should contribute substantially to reducing or preventing the adverse impact of the current or expected future climate, or the risks of such adverse impact, whether on that activity itself or on people, nature or assets.'

Figure 1 below shows the full classification of climate-related hazards as given in Table 5 of the EU Taxonomy legislation. These are categorised into temperature, wind, water and solid mass-related columns, with each then classified as either a chronic or an acute hazard

Figure 1: EU Taxonomy Table 5 – Classification of climate-related hazards (with priority hazards highlighted in blue)

	Temperature related	Wind related	Water related	Solid mass related
Chronic	Changing temperature (air, freshwater, marine water)	Changing wind patterns	Changing precipitation patterns and types (rain, hail, snow/ice)	Coastal erosion
	Heat stress		Precipitation and/or hydrological variability	Soil degradation
	Temperature variability		Ocean acidification	Soil erosion
	Permafrost thawing		Saline intrusion	Solifluction
			Sea-level rise	
			Water stress	
Acute	**Heat wave**	Cyclone, hurricane, typhoon	**Drought**	Avalanche
	Cold wave / frost	**Storm (blizzards/ dust / sandstorms)**	**Heavy precipitation (rain/hail/snow/ice)**	Landslide
	Wildfire *	Tornado	**Flood (coastal, fluvial, pluvial, groundwater)**	**Subsidence**
			Glacial lake outburst	

The list of climate-related hazards in this table is non-exhaustive, and constitutes only an indicative list of the most widespread hazards that are to be taken into account as a minimum in the climate risk and vulnerability assessment.

Whilst all hazards in Figure 1 can affect the built environment depending on the location and context, 6 hazards have been highlighted in blue in the table to denote them being **'priority hazards'** for buildings. These are hazards that significantly **impact** a **building** and its **users** and are typical across the EU.

The climate-related hazards listed in Table 5 may also pose **secondary impacts on the built environment.** Heavy precipitation may increase the chance of damp and mould in buildings. Variations in temperatures and milder winters may increase the spread of vector-borne diseases or pests. Drought conditions may increase the risk of soil shrinkage and subsidence. Whilst these secondary impacts or risks are not included within the EU Taxonomy classification, they must also be considered within adaptation strategies.

***Note**: Wildfires are becoming increasingly common in Europe. The effectiveness of building-scale adaptation measures against wildfires is somewhat limited; once a fire reaches a building and its immediate surroundings very little can be done to enable the building and its occupants to continue operating safely. Adaptation measures against wildfires are most successful at the urban or regional scale. Wildfire is therefore not categorized as a priority hazard within this building adaptation-focused guidance.

An overview of general adaptation measures against wildfires is included within this guide, in a later section on temperature-related hazards.

Building-scale climate adaptation solutions

The technical guidance outlined in this document is focused on adaptation solutions for **individual buildings**. It considers adaptations to the building and its immediate surroundings or plot.

That said, it is important to recognise that the vulnerability of a building is greatly influenced by its wider context. Was the building built on a flood plain? How is the surrounding community or town handling storm water? What measures have been implemented to protect the region from drought?

Urban planners, policy makers and local authorities have the possibility to anticipate and influence adaptation solutions at the neighbourhood, city and regional level. Many resources including the European Commission's **Climate Adaptation in Cities** platform and the Covenant of Mayors for Climate at Energy's **Urban Adaptation Support Tool** provide guidance on neighbourhood- and city-scale climate adaptation strategies.

Building adaptation solutions, combined with wider master planning measures, will have the greatest effect on a building's capacity to adapt to future climate conditions.

Minimising carbon emissions

When adapting buildings to climate change, it is essential not over-design and over-specify materials. A balance is required between structural resilience and the embodied carbon emissions of building materials over the full lifecycle of the building.

Where possible, the adaptation or design of a building should seek to limit carbon-intensive materials (e.g. steel and concrete) and high-carbon design decisions unnecessary long spans).

Adaptation hierarchy for buildings

The adaptation solutions described in the Best practice guidance are best implemented following the hierarchy presented in the figure below. This hierarchy combines actions for multiple industry actors and should be reviewed during the planning, design, construction and operational phases of a building.

Integrate climate change adaptation strategies at the **neighbourhood level** that **address a number of hazards.**

Assess opportunities to **retrofit and adapt existing buildings.** Ensure adaptation strategies **preserve** and **protect cultural values** and the **built heritage.**

Plan the building location, orientation and shape to **minimise exposure to hazards** and consider the **sensitivity** of **users.**

Design passive building systems to either **mitigate hazard risks** or **enable an adaptive management** of **risks.**

Implement building solutions that require **active operation** or **maintenance to mitigate** or **control risks.**

Climate vulnerability and risk assessment for buildings

A holistic and multi-disciplinary climate vulnerability and risk assessment is recommended prior to designing technical adaptation solutions on any building. This guide is specifically focused on climate-related risks. However other hazards such as earthquakes or pests and diseases spread by climate change may be relevant to include in a building vulnerability and risk assessment.

The built environment is particularly at risk from climate change, with considerable potential damages and losses to buildings. The Intergovernmental Panel on Climate Change (IPCC) Assessment Report 6 (AR6) states that:

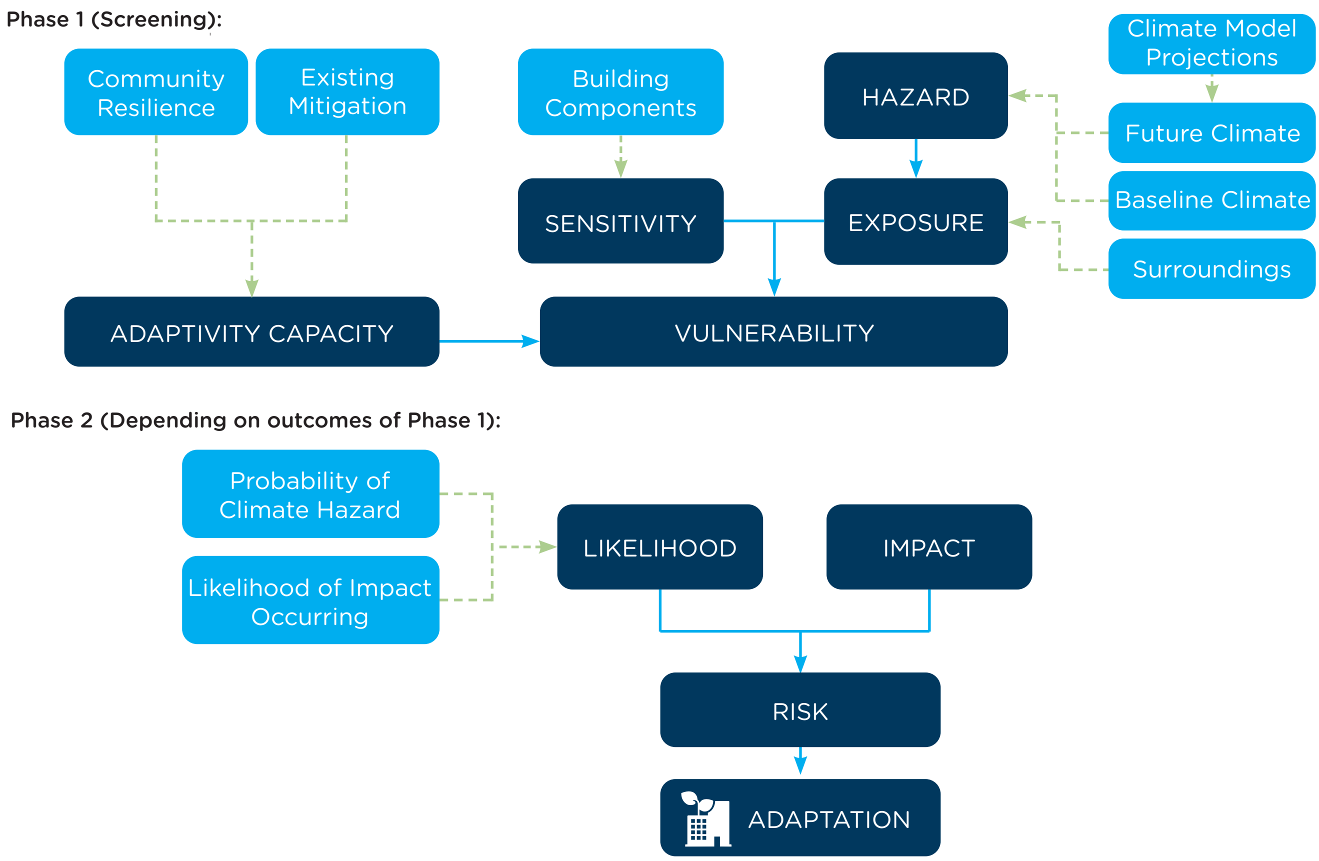
'Information on climate risks needs to be embedded into the architectural design, delivery and retrofitting of housing.'

Climate vulnerability and risk assessment (CVRA) is an effective tool to determine the relevant climate hazards to a building and inform the implementation of adaptation measures.

There are many existing approaches to undertaking a CVRA; however, few relate specifically to buildings. This study has developed a building-specific climate vulnerability and risk assessment methodology, adapted from the from European Commission (2021) Climate proofing of infrastructure.

Full details of this methodology are provided in Chapter 3: Climate vulnerability & risk assessment methodology overview. The methodology to be undertaken, in two phases, is illustrated in the figure below.

Figure 2: Building-specific climate vulnerability and risk assessment



Climate risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence.

As climatic conditions will be changing over the lifetime of a building, future risks need to be considered alongside current risk levels. Therefore, adaptable building design helps ensure that future risks can be addressed and mitigated for the following climate hazards. Detailed information on this overarching solution can be found in **indicator 2.3** of the Level(s) framework.

Future climate impacts

The following best practice guidance addresses a series of climate hazards that currently occur, or will occur, due to climate change (with a certain level of scientific confidence) in specific climatic regions or zones.

This report is intended for Member States of the European Union, and therefore focuses on three climatic regions: western and central Europe, northern Europe and the Mediterranean. Each of these regions experience different climatic conditions and hazards, which are anticipated to change in the future.

The Intergovernmental Panel on Climate Change (IPCC) Working Group I (WGI) has created an **interactive atlas** that synthesises the findings of the IPCC Sixth Assessment Report. This atlas provides a summary of changes in climatic impact drivers (CIDs) for each climatic region.

These climatic impact drivers are organised in the following six categories:

Heat & Cold	Mean air temperature; extreme heat; cold spell; frost.	**Snow & Ice**	Snow, glacier and ice sheet; permafrost; land and sea ice; heavy snowfall and ice storm; hail; snow avalanche.
Wet & Dry	Mean precipitation; river flood; heavy precipitation and pluvial flood; landslide; aridity; hydrological drought; agricultural and ecological drought; fire weather.	**Coastal**	Relative sea-level; coastal flood; coastal erosion; marine heatwave; ocean acidity.
Wind	Mean wind speed; severe windstorm; tropical cyclones; sand and dust storm.	**Other**	Air pollution weather; atmospheric CO_2 at the surface; radiation at the surface.

Future changes in climatic impact drivers refer to a 30–20 year period centred around 2050 and/or consistent with 2 °C gglobal warming, compared to a similar period between 2014 and 1960 or 1900 and1850. In all cases, the information is representative of average changes over the whole region.

The following sections provide an overview of future climate changes anticipated for each region.

Northern Europe

In the western part of northern Europe, climates vary from maritime to maritime subarctic climates. The northern and central areas of the Northern European region are characterised by subarctic climates. Summers in this region are typically mild and humid. Winters are typically humid and cold, with snow covering the ground in the most northern areas.

Heat & Cold

- Mean **surface temperature** and **extreme heat** events are anticipated to **increase**, with a high level of confidence.
- **Cold spells** and **frost events** are predicted to **decrease** with a high level of confidence.

Wet & Dry

- **Mean precipitation levels** have been increasing and will continue to do so, with a high level of confidence.
- **Heavy precipitation** and **pluvial flooding** have been **increasing** and will continue to do so, with a high level of confidence.
- **River flooding** has been **decreasing** and may, with a medium level of confidence, continue to do so.
- There is low confidence in the direction of change for the quantity of landslides, aridity, droughts (hydrological, agricultural and ecological) and fire weather.

Wind

- A **downward trend** has been observed in **mean wind speed,** which is expected to continue with medium confidence.
- **Severe windstorms** may **increase**, with a medium level of confidence.
- Tropical cyclones and sand and dust storms are not relevant in this climatic zone.

Snow & Ice

- A **decrease** in **snow, glacier, ice sheet,** and **permafrost,** and lake, river and sea ice has been observed. This trend is expected to carry on in the future with a high level of scientific confidence.
- There is low confidence in the direction of change for heavy snowfall, ice storms, hail and snow avalanches in this climatic zone.

Coastal

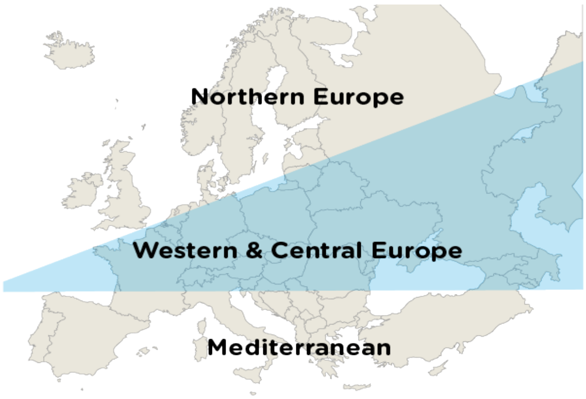
- Relative **sea-level, marine heatwave** and **ocean acidity** are all predicted to **increase** in the future, with a high level of confidence.
- There is no past noticeable trend in coastal flood and erosion but there is high confidence in their future increase.

Source: IPCC Interactive Atlas Regional Synthesis

Western & Central Europe

Western Europe has an oceanic climate influenced by the Gulf Stream. The region is characterised by cool to warm humid summers and cool, wet winters with often overcast skies. Prolonged frost periods are rare. Hot summers have historically been rare;, however heat waves have increased in frequency and intensity in recent years.

Central Europe is characterized by a more continental climate, with colder long-lasting winters and hot summers.



Heat & Cold

- **Mean surface temperatures** and **extreme heat events** have been observed to be **increasing**. These are anticipated to continue increasing in the future, with a high level of confidence.
- **Cold spells** and **frost events** are predicted to continue **decreasing** in the future, with a high level of confidence.

Wet & Dry

- **Mean precipitation levels** have been increasing but there is a low level of confidence in future change.
- **River flooding, heavy precipitation** and **pluvial floods** have been **increasing** and will continue to do so, with a high level of confidence.
- **Hydrological, agricultural** and **ecological droughts** and **fire weather** is expected to increase with medium confidence.
- There is low confidence in the direction of change in landslide and aridity.

Wind

- **Mean wind speeds** have been observed to be **decreasing**, however there is low confidence in the direction of future changes.
- **Severe windstorms** may **increase**, with a medium level of confidence.
- There is a low level of confidence in the direction of change in sand and dust storms. Tropical cyclones are not relevant in this climatic zone.

Snow & Ice

- A **decrease** in **snow, glacier, ice sheet, and permafrost**, and **lake, river** and **sea ice** has been observed. This trend is expected to carry on in the future with a high level of scientific confidence.
- There is low confidence in the direction of change for heavy snowfall, ice storms, hail and snow avalanches in this climatic zone.

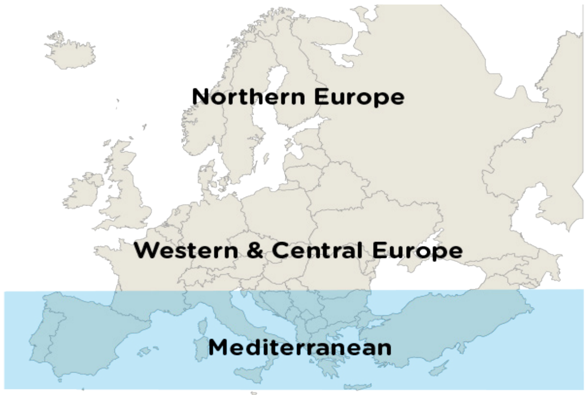
Coastal

- An **upward trend** has been observed in **relative sea-level, marine heatwave** and **ocean acidity**, which is predicted to continue upwards in the future with a high level of confidence. Whilst there is no past noticeable trend in **coastal flood** and **erosion**, there is high confidence in their **future increase.**

Source: IPCC Interactive Atlas Regional Synthesis

Mediterranean

The Mediterranean climate is characterized by dry summers and mild, wet winters and a generally hilly landscape. In the dry summer months, precipitation can become extremely scarce. Continental areas of the Mediterranean can be particularly hot and semi-arid (Natura 2000, n.d.).



Heat & Cold

- An **upward trend** has been observed in **mean surface temperature** and **extreme heat**, which is predicted to continue upwards in the future with a high level of confidence.
- There has been a **decrease** in **cold spells** in this climatic zone and this is predicted to continue with a high level of confidence. **Frost events** are also predicted to **decrease** with a high level of confidence.

Wet & Dry

- **Mean precipitation levels** are expected to **decrease,** with a high level of confidence for change in the future.
- **River flooding** has been **decreasing** and may, with a medium level of confidence, continue to do so.
- **Aridity, droughts (hydrological, agricultural and ecological)** and **fire weather** are predicted to **increase** in the future, with a high level of confidence.
- There is a low level of confidence in the direction of change for landslides.
- **Heavy precipitation events** and **pluvial flooding** are anticipated to **increase**, with a medium level of confidence.

Wind

- A **downward trend** has been observed in **mean wind speed**, which is expected to continue, with a high level of confidence.
- **Severe windstorms** may **increase**, with a medium level of confidence.
- There is a low level of confidence that the number of sand and dust storms will change. Tropical cyclones are not relevant in this climatic zone.

Snow & Ice

- A **decrease** in **snow, glacier, ice sheet, and permafrost,** and **lake, river** and **sea ice** has been observed. This trend is expected to continue in the future, with a high level of confidence.
- There is a low level of confidence that the quantity of heavy snowfall, ice storms, hail and snow avalanches will change in this climatic zone

Coastal

- An **upward trend** has been observed in **relative sea-level, marine heatwave** and **ocean acidity**, which is predicted to continue upwards in the future, with a high level of confidence.
- There is high confidence in **coastal flood** and **erosion increasing** in the future.

Source: IPCC Interactive Atlas Regional Synthesis

Summary

Each climatic zone within Europe is anticipated to experience an increasing number of heat wave, storm, heavy precipitation, and flooding events. Droughts and wildfires are anticipated to increase in Western & Central Europe, and the Mediterranean in particular.

Best practice building adaptation solutions will therefore have to improve resilience against these climate-relates hazards.

Climate adaptation strategies & historic buildings

Strategies to renovate and retrofit existing buildings, whilst reducing their vulnerability to climate hazards, are essential. The need to adapt and protect historical and cultural heritage buildings is particularly acute, and complex.

It is estimated that 68 million of Europe's buildings are traditional or historic constructions. These hold deep cultural value, but the majority do not have statutory protection (EU OMC, 2022).

Some climate-adaptation solutions are naturally part of traditional buildings, such as natural passive ventilation, window shutters and cross-bracing in timber roof trusses. These effective climate-adaptation features should be maintained and repaired wherever possible.

However, these solutions are not always appropriate to be applied to existing buildings or built heritage.

Historical buildings are particularly vulnerable to **maladaptation**, where climate-adaptation measures may have an unintended effect, leading to increased vulnerability.

For example, measures that affect the physical structure, appearance or material composition of an existing building may have a negative impact on the building's authenticity and cultural heritage value.

Similarly, alterations to historical building fabric (aiming to insulate or waterproof a building) may fail to take account of the hygrothermal properties of traditional constructions (EU OMC, 2022).

Historic buildings require a more sensitive use of innovative measures and concepts than those used for more recent building stock and new constructions.

Any historical building adaptation should therefore ensure measures are:

- **respectful of the nature of heritage buildings;**
- **fully compliant with local regulations;**
- **developed in collaboration with professional local expertise from the earliest stages of decision making**.

General best practice and technical guidance for traditional buildings is provided in each of the priority hazard sections.

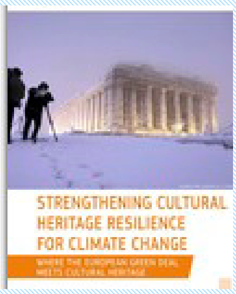
New European Bauhaus Initiative

As part of the Green Deal's **Renovation Wave**, the European Commission has launched the **New European Bauhaus Initiative**.

This initiative aims to act as an incubator of innovation and creativity and to realise environmentally friendly and climate protection-oriented renovations in the building stock at a larger scale without impairing the historic character of European cities and landscapes.

Strengthening cultural heritage resilience for climate change

The European Commission has also published **'Strengthening cultural heritage resilience for climate change'** summarising good practice and innovative measures for safeguarding cultural heritage in relation to climate change.



Principles for EU-funded interventions with potential impact on cultural heritage

provides a **summary** of key concepts, European and international conventions, standards and practices in heritage conservation.

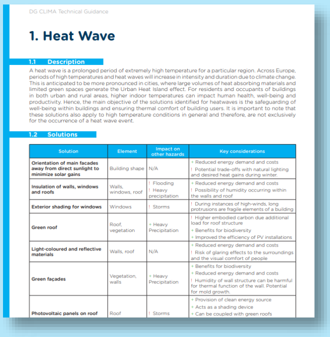
Best practice guidance

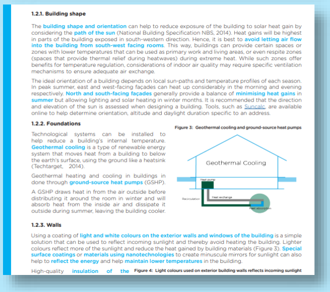
Within this Best practice guidance, priority hazards are defined as climate-related hazards that are typical across Europe, which significantly impact a buliding and its users. This is intended to align with the EU Taxonomy-defined climate-related hazards.

The following sections present building-scale adaptation solutions for each of the priority hazards in turn. A later section outlines building adaptation solutions for further climate-related hazards.

How to use the guide

Each of the following priority hazard sections are structured into four parts:


1. Heat Wave
1.1 Description
1.2 Solutions



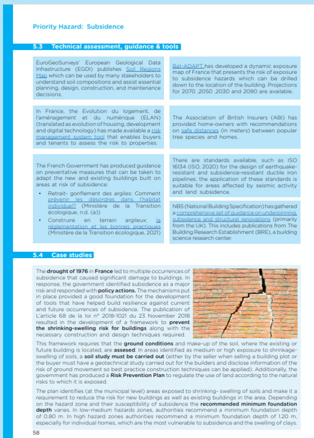
Description

An overview of the priority hazard and the impact it has on the built environment's wellbeing of building users is presented in the first section.

Solutions

A comprehensive set of solutions are identified for each part of the building:

- Building shape
- Foundations
- Walls & windows
- Roof
- Vegetation
- Preferred materials
- Space considerations
- Primary structure
- Services
- Other

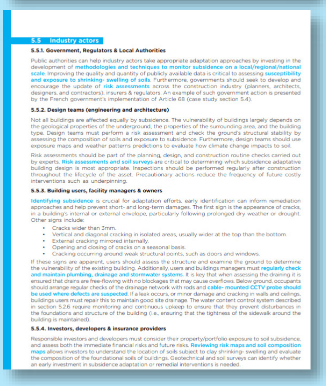

Priority Hazard: Subsidence
5.3 Technical assessment, guidance & tools
5.4 Case studies

Technical assessments, guidance & tools

Useful resources including tools, standards, certifications and guides for building owners and users are provided.

Case studies

Innovative applied examples of climate adaptation solutions are showcased as case studies.


5.5 Industry actors

Industry actors

Collaboration and participation from actors involved in building construction and renovation is key to driving the implementation of the adaptation approaches in this guide. However, it is not always clear for industry actors what their scope of intervention is or how they can support adaptation efforts.

The final section includes a series of actions and considerations for:

- Government, regulators & local authorities;
- Design teams;
- Building users, facility managers & owners;
- Investors, developers & insurance providers.

Adapting buildings to priority hazards

This section evaluates best practice building adaptation solutions for each priority hazard, i.e., those hazards that significantly impact a building and its users. The hazards evaluated are:

Heat wave	**Flooding**
Storms	**Subsidence**
Heavy precipitation	**Drought**

These are all categorised as acute hazards by the EU Taxonomy (Figure 1).

Adapting to multiple climate hazards

Each of the climatic zones across Europe is anticipated to experience an increasing number of heat waves, storms, heavy precipitation and flooding events. Effective adaptation measures will therefore need to be resilient to multiple hazards.

However, implementing climate adaptation solutions against one hazard may affect a building's ability to respond to other hazard events. An adaptation intended to improve a building's response to low temperatures, for example, may have an adverse effect on the building's ability to respond to high temperatures or a heat wave. These **unintended impacts** and **interactions** are important to consider when planning and designing adaptation solutions. Each solution proposed in this report is therefore critically evaluated on a case-by-case basis to identify both the positive and negative impacts it may have on a building.

+ A plus symbol highlights when a solution may have a beneficial impact in responding to other hazards.

! An exclamation point highlights potentially negative effects from a solution. This interaction should be carefully considered before implementing the solution.

Adapting and renovating existing buildings

Many of the adaptation solutions proposed in this report may be applied to an existing building as part of retrofit or renovation. However, it is important to assess the suitability of retrofitting solutions on a case-by-case basis. Further technical assistance from design or engineering professionals is recommended before implementing a solution as part of a building's retrofit.

Solutions that are not suitable for a retrofit or renovation are marked with the following icon: 

1. Heat wave

1. Heat wave

1.1 Description

A heat wave is a prolonged period of extremely high temperature for a particular region. Across Europe, periods of high temperatures and heat waves will increase in intensity and duration due to climate change. This is anticipated to be more pronounced in cities, where large volumes of heat-absorbing materials and limited green spaces generate the urban heat island effect. For residents and occupants of buildings in both urban and rural areas, higher indoor temperatures can impact human health, well-being and productivity. Hence, the main objective of the solutions identified for heat waves is the safeguarding of well-being within buildings and ensuring thermal comfort for building users. It is important to note that these solutions also apply to high-temperature conditions in general and are therefore not exclusively for the occurrence of a heat wave event.

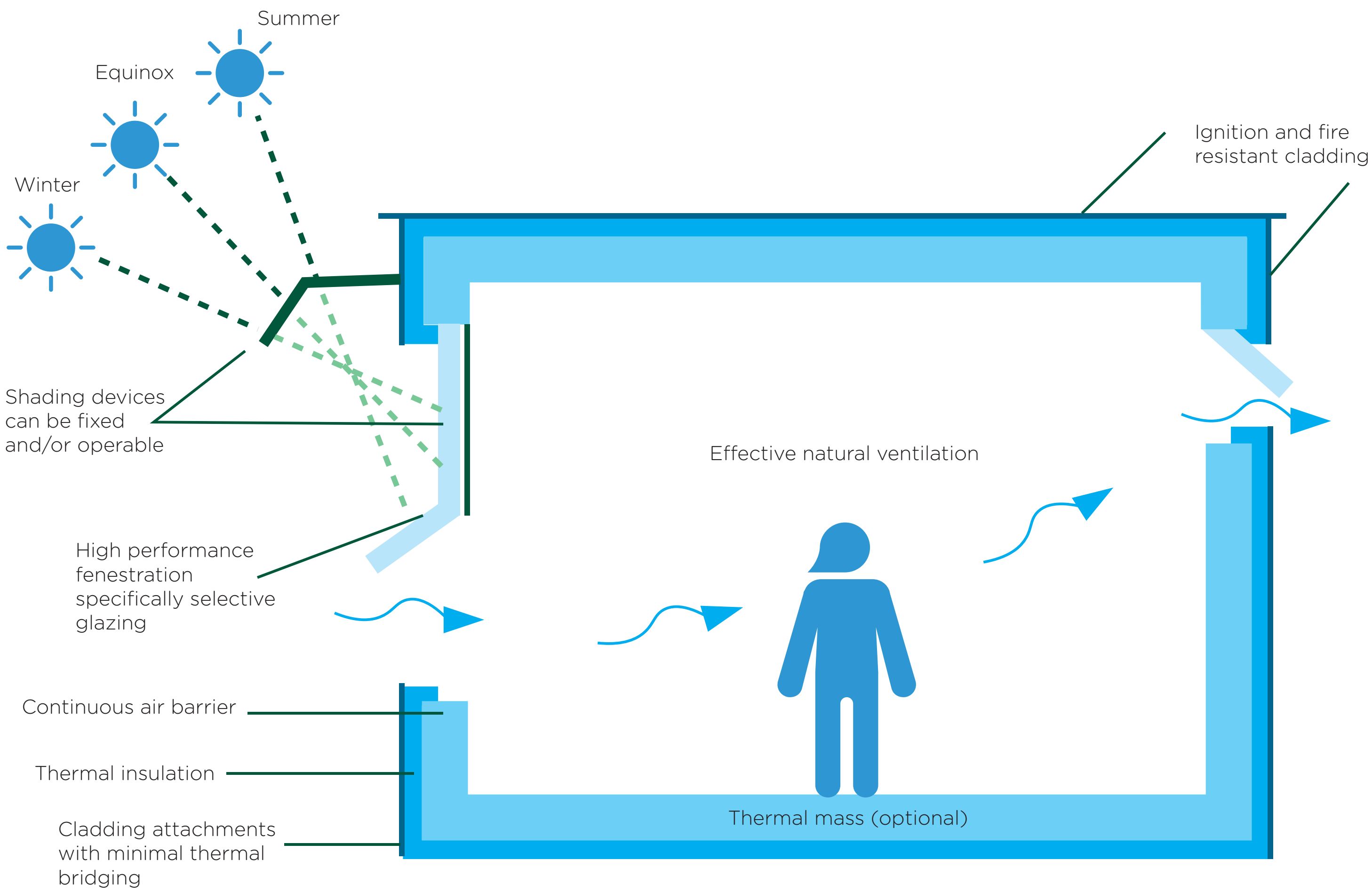
1.2 Solutions

Solution	Element	Impact on other hazards	Key considerations
Orientation of main facades away from direct sunlight to minimise solar gains	Building shape	N/A	+ Reduced energy demand and costs ! Potential trade-offs with natural lighting and desired heat gains during winter Not suitable for a retrofit or renovation
Insulation of walls, windows and roofs	Walls, windows, roof	! Flooding ! Heavy precipitation	+ Reduced energy demand and costs ! Possibility of humidity occurring within the walls and roof
Exterior shading for windows	Windows	! Storms	! During instances of high winds, long protrusions are fragile elements of a building
Light-coloured and reflective materials	Walls, roof	N/A	+ Reduced energy demand and costs ! Risk of glaring effects to the surroundings and the visual comfort of people
Photovoltaic (PV) installations on roof	Roof	! Storms	+ Provision of clean energy source + Acts as a shading device + Can be coupled with green roofs ! Should be impact-resistant in storm and hail-prone regions
Green roof	Roof, vegetation	+ Heavy precipitation	! Higher embodied carbon due to additional load for roof structure + Benefits for biodiversity + Improved the efficiency of PV installations
Green facades	Vegetation, walls	+ Heavy precipitation	+ Benefits for biodiversity + Reduced energy demand and costs ! Humidity of wall structure can be harmful for thermal function of the wall Potential for mould growth.
High vegetation on sun-exposed sides of the building to provide shading (exterior)	Vegetation	+ Heavy precipitation + Flooding ! Storms ! Subsidence	+ Benefits for biodiversity + Reduced energy demand and costs ! Risk of vegetation being uprooted during storms ! If roots are too close they expose foundations to higher risk of subsidence
Passive ventilation through thermal chimneys	Space considerations	N/A	+ Reduces energy demand for cooling and ventilation Not suitable for a retrofit or renovation

Priority hazard: Heat wave

Solution	Element	Impact on other hazards	Key considerations
Temperature zones (preventing flow of heated air)	Space considerations	N/A	+ Potential trade-offs with natural and desired heat gains during winter
Thermal mass and phase-change materials	Preferred materials	N/A	+ Reduced energy demand and costs ! High embodied carbon from materials with high inertia
Natural ventilation	Space considerations	N/A	+ Reduced energy demand and costs
Movement joints	Structure	+ Subsidence	+ Protect buildings from cracking due to high temperature variability
Active cooling and ventilation	Services	! Storms ! Flooding ! Heaving precipitation	+ Provides immediate cooling in periods of extreme heat ! Standing water from flooding might damage the electrical components ! Driving rain may cause damage
Geocooling and heat pumps	Other	N/A	! Consideration of energy source for the heat pump
Connection to district cooling	Other	N/A	! Requires installation of neighbourhood-scale network

Figure 3: Overview of different adaptation solutions to heat waves.



1.2.1. Building shape

The **building shape and orientation** can help to reduce exposure of the building to solar heat gain by considering the **path of the sun** (National Building Specification, 2014). Heat gains will be highest in the parts of the building exposed to a southwestern direction. Hence, it is best to **avoid letting air flow into the building from southwest facing rooms**. This way, buildings can provide certain spaces or zones with lower temperatures that can be used as primary work and living areas, or even respite zones (spaces that provide thermal relief during heat waves) during extreme heat. While such zones offer benefits for temperature regulation, considerations of indoor air quality may require specific ventilation mechanisms to ensure adequate air exchange.

The ideal orientation of a building depends on local sun-paths and temperature profiles for each season. In peak summer, east and west-facing facades can heat up considerably in the morning and evening respectively. **North and south-facing facades** generally provide a balance of **minimising heat gains** in **summer** but allowing lighting and solar heating in winter months. It is recommended that the direction and elevation of the sun are assessed when designing a building. Tools, such as Suncalc, are available online to help determine orientation, altitude and daylight duration specific to an address.

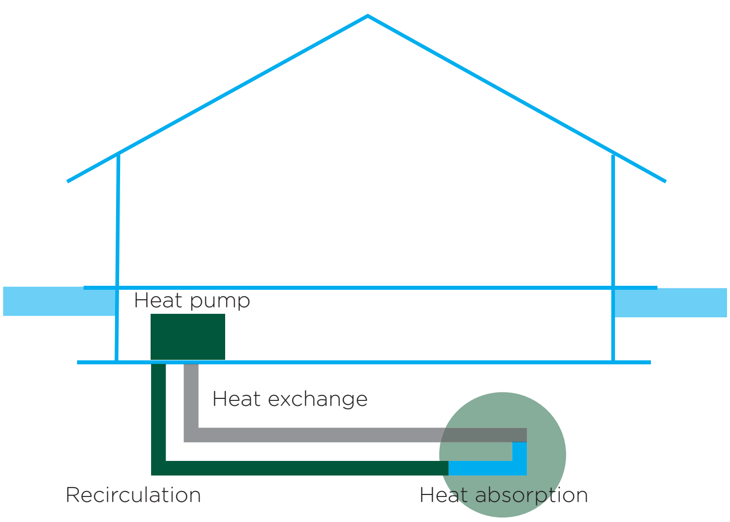
1.2.2. Foundations

Technological systems can be installed to help reduce a building's internal temperature. **Geothermal cooling** is a type of renewable energy system that moves heat from a building to below the earth's surface, using the ground like a heat sink (Techtarget, 2014).

Geothermal heating and cooling in buildings is done through **ground-source heat pumps**. (see Figure 4).

A ground-source heat pump draws heat in from the air outside before distributing it around the room in winter, and will absorb heat from the inside air and dissipate it outside during summer, leaving the building cooler.

Figure 4: Geothermal cooling and ground-source heat pumps



1.2.3. Walls

Using a coating of **light and white colours on the exterior walls and windows of the building** is a simple solution that can be used to reflect incoming sunlight and thereby avoid heating the building. Lighter colours reflect more of the sunlight and reduce the heat gained by building materials (Figure 5). **Special surface coatings** or **materials using nano-technologies** to create minuscule mirrors for sunlight can also help to **reflect the energy** and help **maintain lower temperatures** in the building.

High-quality **insulation of the building envelope** is crucial to delay heat gain of the building fabric during heat waves. However it is important to ensure that **thermal bridges** are **avoided**. Thermal bridges typically occur where there is either a break in the insulation, less insulation or the insulation is penetrated by an element with a higher thermal conductivity (BREGroup, n.d.). Thermal bridges should be avoided particularly around windows and at the junction between floors and walls. Design elements to tackle this may include cladding attachments. Not only do these reduce thermal bridging but also improve wall assembly thermal performance.

Figure 5: Light colours used on exterior building walls reflects incoming sunlight

1.2.4. Windows

Windows are the main entry point for sunrays and heat energy in the building. The glazing ratio, or the proportion of glazing to opaque surface in a wall (also known as window-to-wall ratio), should therefore **be carefully considered to limit solar gain** whilst still maintaining appropriate daylighting for well-being (BRE, 2022). The optimal ratio of glazed facade surface to non-glazed surface depends on local climate conditions and regulations. It is also possible to use low solar-gain glazing or smart glass that darkens and brightens automatically, controlling the penetration of the solar radiation. High-performance glazing should be a priority in retrofitting buildings (with the exception of heritage buildings where the windows hold cultural value).

To make designs more energy efficient, it is possible to use glass that is printed with a ceramic frit and fired into a permanent, opaque coating. **Fritted glass** helps reduce glare, cuts cooling costs, and lowers the danger to birds (Stamp, 2016).

Windows are critical for effective natural ventilation of a building. In particular, the night time removal of hot indoor air through windows is essential (see Section 1.2.7). Ventilating or cooling a building with no energy consumption as part of a design feature is referred to as **passive ventilation** (See Figure 6). Passive ventilation may be achieved through either **cross** or **stack ventilation** (Figure 6). Cross ventilation relies on placing windows or openings on opposite facades of the building, with ventilation being driven by exterior wind or airflow. Stack ventilation relies on openings that are placed at different heights in the facade or roof; air flows between the openings as a result of the thermal difference between the indoors and outdoors temperate allows the air to flow. As the warmed air rises up through a central space, it draws more air in at the bottom in a convection process.

A **solar** or **thermal chimney** (generally tall wide structures constructed facing the sun, designed to absorb solar radiation) uses a similar process as stack ventilation. Solar chimneys are particularly effective in climates that are humid and hot (Designing Buildings, 2022). It is important that the chimney is insulated from the building itself so that the heat gains do not transmit into occupied spaces.

Passive cooling is a measure that uses no energy to cool buildings. It involves **solar -shading installations** that reduce automatically or manually the amount of heat and light entering the building.

Installations can include **external window shutters** and **brise-soleil features** above glazing (Figure 7).

Additionally, **window blinds** can also be used inside the building but are not as effective in reducing thermal gain as the heat energy has already entered the internal space.

Figure 6: Passive ventilation techniques reduces indoor temperatures

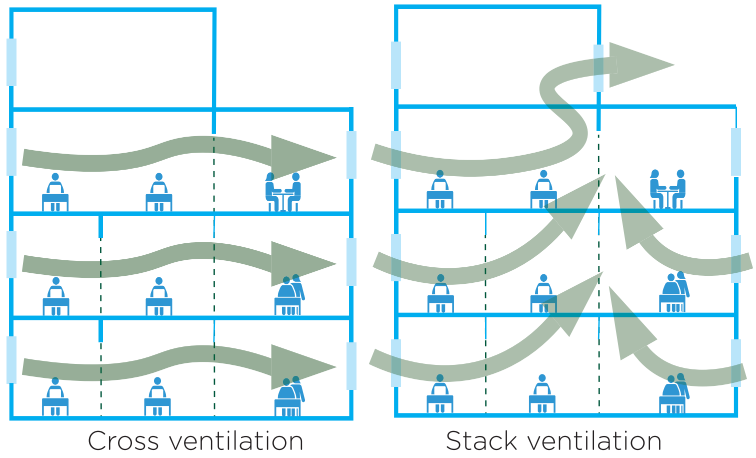
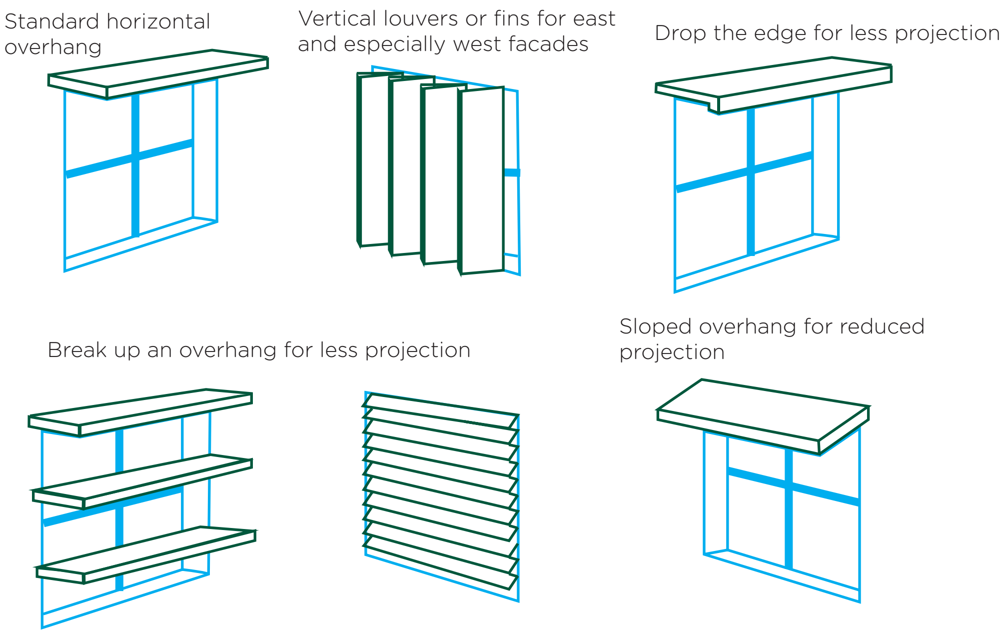


Figure 7: Mechanism of overhang shading and other different shading installations



The overheating solutions presented in this chapter **may not be appropriate for heritage buildings** as external and internal solutions may conflict with historic characteristics. Alterations to the building fabric are likely to also erode historical significance. In some cases, heritage buildings have existing measures that help with adaptation to heat waves and overheating. For example, **sash and case windows** are a common feature of traditional buildings. These should be **maintained** where possible, to ensure that the top and bottom sashes are openable in such a way that effective air circulation and low-level background ventilation is maintained. In traditional windows, **shutters** may be set into the window reveals to prevent overheating by controlling sunlight. If not, these may be re-instated with low levels of intervention to reduce the need for mechanised cooling. Installing roller blinds may also be effective in helping to reduce solar gain and glare (Historic Environment Scotland, 2017).

1.2.5. Roof

Having **light colours** and **reflective materials** (such as **solar-reflective tiles**) on the building's roofing can increase its albedo and reduce the heat island effect.

Green roofs (Figure 8) help lower the indoor temperature of buildings because soil has a high capacity for heat storage and foliage acts as a shading device that absorbs thermal energy through photosynthesis (Marvuglia, Koppelaar and Rugani, 2020). The plants used on green roofs should be carefully selected to respect local species, have a positive impact on biodiversity and lower heat gain as much as possible. Plants like salvia and stachys are found to be particularly effective at lowering buildings' temperature (Vaz Monteiro et al., 2017). Moreover, evapo-transpiration of water from plants and soil can regulate the local microclimate, thus supporting adaptation efforts on a wider scale. Green roofs can also help reduce storm water runoff generated during heavy precipitation events, therefore offering benefits against multiple climate hazards. Refer to Section 2.3 for more information.

The **installation of photovoltaic (PV) panels** on roofs not only generates renewable electricity but also keeps the building shaded and cool. This solution offers important co-benefits for the reduction of greenhouse gas (GHG) emissions (Figure 9).

Photovoltaic panels and green roofs can be combined to improve the performance of solar panels by an average of 4 %. Vegetation surrounding solar panels on roofs can help keep the air clean from dust and pollutants, maintaining the effectiveness of photovoltaic panels (Irga et al., 2021). Vegetation also helps to keep surrounding temperatures low which limits overheating the panels, leading to increased performances (Peacock, 2021).

Green roofs and **solar panels** will **increase** the loading to roofs which may result in additional material required and **higher embodied carbon.** Solutions to reduce the structural material and associated embodied carbon should be explored. This could include: reducing the depth of substrate in a green roof, using suitable planting to reduce water storage requirements at roof level or using a pitched roof to allow light-weight PV panels to be utilized.

Figure 8: Green roofs insulate the building and create cooler microclimates

Figure 9: PV installations on the roof reduce heat gains of the building while supplying renewable energy

1.2.6. Vegetation

Green facades can provide heat reduction benefits similar to green roofs, by blocking and transforming sunlight and cooling the building's microclimate. Green facades can be created on external walls, with either lightweight structures allowing plants to grow directly on the facade, or by plants growing from the bottom of the building, climbing up the wall.

Careful consideration in designing the green facade is required as the humidity of a green wall structure can be harmful to the thermal function or integrity of the wall. This is explored further in Section 3.2.3

As part of the landscape, planting trees on the sides of buildings that are most exposed to sunlight during the day supports adaptation by offering protection from direct sunlight to the facades, and providing shade around the building (shown in Figure 10).

This solution can result in reduced heat absorption and heat radiation of the building's fabric, as well as the potential to reduce the urban heat island effect. This solution also offers co-benefits by supporting adaptation measures to water-related hazards and enhancing biodiversity (C2ES, 2017) (see Figure 11).

Trees planted in eastern, southern and western directions provide the most shading. The choice of deciduous plants (as opposed to coniferous trees) offers higher protection from sunlight in summer while enabling heat gains in winter months when they lose their leaves.

Additionally, planting shrubs and grass provide cooling through evapotranspiration. Evapotranspiration, alone or in combination with shading, can help reduce peak summer temperatures by 1 to 5 °C.

Figure 10: Exterior vegetation provides shading to the building and its users.

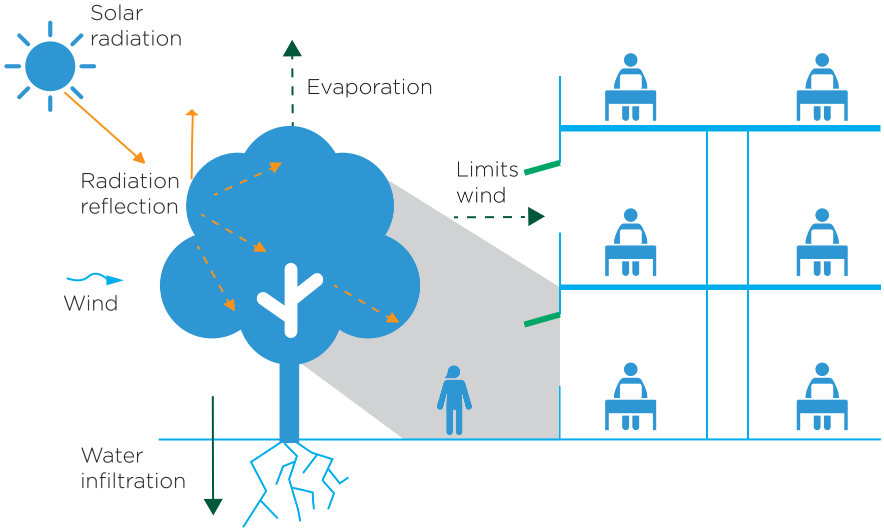


Figure 11: Planting shrubs and grass can provide cooling via evapotranspiration.

1.2.7. Preferred materials

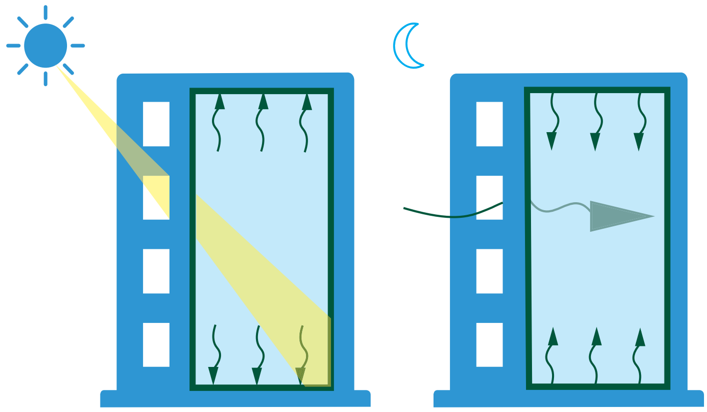
As described under the walls and windows sections, **surface coating and reflective materials** are key adaptation solutions. When selecting materials and their characteristics, additional measures to consider are their thermal mass. Materials with high thermal mass such as concrete slabs, masonry and timber frame walls, and tiles have the ability to absorb and store heat (both sunlight and internal gains) (Reardon and Marlow, 2020).

Different thermal mass materials absorb varying amounts of heat and take longer (or shorter) to absorb and re-radiate it (Smarter Homes, 2017) .

High thermal mass materials will absorb and release the heat slowly, thereby regulating temperatures over time, making the inside of a building cooler during the day and warmer during the night (Figure 12). The release of heat overnight makes the building warmer during this timeframe and hence it is important to have appropriate ventilation during the night.

Adobe walls offer a durable and low-carbon high thermal mass material option (Olukoya Obafemi & Kurt, 2016).

Figure 12: Thermal mass helps regulate indoor temperatures



1.2.8. Space consideration

Trees and vegetation around the building offer protection from direct sunlight and provide shade to a building, when planted in strategic locations. They can also be used to shade pavement in parking lots.

Additional outdoor cooling solutions may be provided by shading mechanisms around the building.

1.2.9. Primary Structure

The use of thermal mass from the primary structure, with active strategies such as **chilled beams** can control overheating. Ventilation strategies could make use of **thermal structures in the basement** to cool external air flowing into the building (Minson, 2019). The **additional load** of any of these **cooling strategies** should be accounted for when designing the primary structure of the building.

When buildings, particularly large ones, are exposed to high temperature variability, attention must be paid to the **frequency** and **position** of **joint movements**. This can be particularly prevalent during the construction of the building, before the building is thermally stable.

Some forms of construction, particularly in traditional buildings, may have a permeable building envelope (as opposed to a fully-sealed envelope). Therefore, adding insulation and vapour barriers to permeable walls to regulate temperatures could significantly increase indoor humidity, leading to moisture and dampness. Professional guidance should be sought when adapting a building for overheating, to avoid maladaptation.

Variations in temperature and atmospheric humidity can also have a significant impact on the deterioration of a building structure. An increase in temperature will accelerate the corrosion and deterioration of concrete, steel and reinforcement (Raposo, et al, 2020). This can affect the limit states of a building design and reduce the building's service life.

Solutions to avoid structure deterioration due to humidity within the building are detailed in Section 3 (Heavy precipitation).

1.2.10. Services

During the operational phase of the building, the use of efficient **active cooling** and **ventilation mechanical systems** may be used to improve thermal comfort during peak heat times. Active cooling solutions could involve air-conditioning systems, geothermal cooling, ground coupling or forced ventilation. When installing air-conditioning, the use of renewable energy should be prioritised to ensure that active cooling does not contribute to increasing GHG emissions and adversely impact climate change mitigation strategies. Additionally, the energy use of active cooling can be reduced through the use of **fans** that provide sufficient ventilation cooling in medium heat.

Some traditional and heritage buildings have the inherent property of **passive cooling** and ventilation. However, these features can get overlooked in refurbishment projects, with mechanical systems being implemented instead. Therefore it is important to ensure that vents, such as heritage cast iron vents, are not blocked, chimney flues are open and chimney balloons removed or deflated during summer months.

1.2.11. Other

District cooling networks have been created in many southern European cities. In these systems, excess cooling capacity from industrial activities is pumped via a network to connected buildings. District cooling systems play a key role in reducing energy consumption, they have the potential to reduce energy consumption by around 5% compared to conventional air-cooled chilled water systems (GlobalABC, 2021). Additionally, **heat exchangers** can then use this cooling potential as an energy efficient cooling source for air-conditioning systems.

During daytime, **cooling from water** can be used to amplify cooling. For example, this could be combined with cross-ventilation by allowing incoming air to flow over a water body or through a curtain of pulverised water , which cools it before entering the internal spaces. To avoid high humidity, a heat exchanger can be used. In that case air exiting the building is cooled down with water and inflowing air can be cooled with the outflowing air.

In heritage buildings it is important that **exposed domestic hot water pipes** are **insulated**. This prevents heat from dissipating and contributing to the build-up of heat inside the building. Additional measures such as lagging hot water storage tanks will also minimise the amount of heat emitted from plumbing systems.

1.3 Technical assessments, guidance & tools

National and international sustainable building certification tools such as BREEAM, LEED, DNGB, HQE include criteria or recommendations for passive cooling.

Technical Guidance for implementing green roofs and green facades (in German).

The Passive House Standard contains criteria for passive cooling and can be adapted to local climate characteristics.

Forecasting tools for future temperatures such as Weathershift are publicly available.

Climate projection models combined with building specifications to assess the resilience to heat (in French).

The Vienna Burgtheater uses an air well cooling strategy dating from the 19th Century

1.4 Case studies

Cooling Singapore, a large city-wide project that resulted in a catalogue of 86 measures to mitigate the urban heat island effect and improve thermal comfort.

The Vienna Burgtheater uses an air well cooling strategy dating from the 19th Century

SOLAR XXI, an office building in Portugal that combines facades covered in photovoltaic panels, geo-cooling and night-time cooling.

Library of TU Delft, which features a large green roof that is oriented is orientated in a southwestern.

Yale Environment study of white roofs in New York.

1.5 Industry actors

1.5.1. Government, regulators & local authorities

Policymakers and spatial planners can support the adaptation of buildings to heat by developing an encompassing **intervention framework**. This framework should be based on the establishment of standards to prevent overheating in buildings, good quality easily accessible climatic data and campaigns for raising awareness. Pairing **reliable** and **easily accessible data** on climate change risks and vulnerability with **climate change forecasts** enables industry actors to make informed decisions and minimise the possibility of high costs of adaptation due to delayed action.

Policies that facilitate the inclusion of climate risk considerations in standards can help ensure that climate risk is incorporated early in the planning stages. For example, the requirement for appropriate cooling or ventilation installations early in the construction stage can prevent costly renovations in the future. Therefore, **building codes** and requirements for **risk assessment documentation** can have substantial benefits.

Urban planners have the possibility to anticipate and influence adaptation **solutions** at the **neighbourhood level** to enable individual buildings to make use of larger structures for temperature regulation. Green spaces or networks for airflow and trees along streets for shading of buildings can be implemented at a local level. Similarly, water bodies to cool air can be included in urban development plans and projects.

1.5.2. Investors, developers & insurance providers

Thermal discomfort may reduce the usability of a building and lead to costly refurbishments to implement adaptation solutions at a later stage. It is therefore important for investors, developers and insurance providers to carefully **consider the need for thermal adaptation** from the start of a development project. Requiring a **climate risk assessment process**from design teams is an important first step to understanding these risks. This assessment can inform the development and implementation of adequate adaptation solutions.

Financial institutions offering financial products, such as funds that incorporate real estate, are a key target of regulation at EU level. Certain financial products under the EU Sustainable Finance Disclosure Regulation will be required to disclose on their sustainability implications and have to **assess their assets contribution to climate change adaptation** under the EU Taxonomy. This includes adaptation to heat waves. Therefore, **active adaptation planning**, and the consideration of the adaptation measures explored in this chapter will provide an advance on regulatory requirements for the coming years.

Investors, developers and insurance providers can make use of reporting frameworks such as LEVEL(s). LEVEL(s) is the EU framework for assessing and reporting on the sustainability performance of buildings and the extent to which climate adaptation is incorporated. In fact, one of the six macro-objectives of LEVEL(s) is a healthy and comfortable space that includes a sub-indicator on the degree of thermal comfort. Utilising these reporting frameworks provide valuable information for industry actors to identify sustainable intervention and future-proof their investments.

1.5.3. Design teams (engineering and architecture)

Most of the solutions for adapting buildings to heat waves must be designed and implemented at the planning and design stage. Designers therefore play a crucial role in ensuring that the risk of overheating is assessed, and that adaptation solutions are included in early design stages.

A comprehensive appraisal of adaptation solutions should be conducted by the design team, which is then discussed with the developers to prevent challenges in future heat wave events. This process starts with assessing the risk of overheating (likelihood, extent based on local climate projections and the vulnerability of the planned building), identifying adequate solutions (such as designing in the correct use of thermal mass) and advising clients on these solutions. Furthermore, design strategies should undergo a series of stress tests to demonstrate that they are robust solutions. Design teams can make use of the stress test recommended by Passivhaus. This can be supported by governmental recommendations, public assessment tools and existing case studies.

Dynamic thermal modelling tools should be used to assess the risk of overheating for building designs for new builds or renovations. These tools simulate the internal temperature conditions of a building and can help evaluate whether threshold conditions of discomfort may be reached. Dynamic thermal modelling tools allow for a zonal approach to be taken, examining how different spaces within the building perform. This can allow for a more targeted approach to renovation or remedial works, that minimises disruption to the building (Historic England, 2021).

Emission reduction targets in certain countries have resulted in the building sectors tackling emission reductions by increasing the level of thermal insulation in buildings, as well as increasing the level of airtightness. Buildings that have been insulated and tightly sealed to prevent heat loss during winter, and which lack thermal mass, have little shading and poor natural ventilation, are at risk of overheating during summer. Designers should carefully consider what adaptation solutions can be applied to existing buildings to maintain the building temperature at a moderate level and reduce the need for cooling.

For design teams, heritage buildings may present a complex situation given the sensitivities of the buildings. Heritage buildings should be treated on a case-by-case basis and adaptation solutions carefully considered so they do not compromise the cultural value of the building.

1.5.4. Building users, facility managers and owners

Many adaptation solutions to heat waves and the overheating of indoor areas are decided, and implemented, before the occupation of the building. Nonetheless, the building owners, occupants, and facility managers have important roles in ensuring that these are well maintained and hence effective in tackling overheating and thermal discomfort. This involves **regular maintenance checks** on installed **equipment** as well as **cleaning** and **repairing ventilation systems** to ensure they do not become blocked.

Facility managers and owners can implement **automated & smart building management systems** such as smart thermostats, sensors and automated devices. This helps to optimise shading, ventilation, active cooling and indoor energy.

Building management systems and solutions, such as window blinds and mechanical ventilation, require appropriate operation to contribute optimally to cooling efforts. Hence, providing building users with **training** and **information** how to operate cooling solutions is important to ensure they are working at maximum efficiency. Training and awareness raising includes sharing knowledge of the best times to open windows, identifying which spaces are coolest during peak temperatures, how to maintain cooling in indoor spaces, and the energy-efficient operation of day-to-day equipment to minimise internal heat sources.

Buildings users should consider the **heat being produced by equipment** within the building and consider **measures** to **reduce** this, to ensure thermal comfort.

This could include:

- adjusting the size and quantity of devices;
- choosing equipment that generates little heat (low-energy lighting);
- choosing equipment with high-rated energy labels;
- relocating IT equipment to specialized locations (such as relocating IT servers to collocation sites or the cloud);
- optimising and regulating the use of equipment to avoid unnecessary consumption, developing an awareness strategy for building occupants in order to change behaviours.

2. Storms

2. Storms

2.1 Description

A storm is a generic term to describe a deep and active low-pressure centre combined with strong winds, cloud cover and precipitation (Met Office, 2022). The term 'storm' refers to any strong atmospheric disturbance. This includes high winds (over 100 kilometres per hour), thunderstorms, blizzards (over 56 km/h, with or without snow) (UCAR Centre for Science Education, 2019), tornadoes, cyclones, tropical storms (over 63 km/h), cyclones, typhoons (over 120 km/h), hurricanes (over 120 km/h), and sand or dust storms (WMO, 2020).

The type of storm is determined by its wind speed, size, visibility, the inclusion of lightning, hail, snow, dust, sand, debris, clouds, rain, location (cold/warm sea, mainland, arid/ semi-arid region) (QA International, 2010), temperature and region (North Atlantic, North Pacific, Northwest Pacific, etc.) (NOAA, 2021).

When a building is exposed to a storm, its structure and equipment can get damaged or even torn off, sometimes causing casualties. To avoid this, it is essential to ensure that the building and surrounding equipment can withstand wind pressure and other related hazards. The following sections investigate technical solutions that would lower risks induced by storm events to building elements, i.e. high winds, rain and lightning.

2.2 Solutions

The following technical solutions can be applied in any storm situation, i.e. involving strong winds, rain, hail, snow and lightning. A storm event may involve heavy precipitation (rain, snow and hail), (see Section 3) and flooding or storm surges (Section 4).

Solution	Element	Impact on other hazards	Key considerations
Favour aerodynamic shapes	Building shape	N/A	! Without creating wind tunnels. ! For high-rises, the impact on birds should be assessed
Lowest liveable floor elevated above ground level	Foundations	+ Flooding	! Negative impact on wind loads
Undertake performance-based wind design	Primary structure	N/A	N/A
Limit peak story drift	Primary structure	N/A	N/A
Effective roof drainage system	Roof	+ Heat waves + Heavy precipitation + Flooding	N/A
Changing the size and increasing the frequency of fastenings for roof tiles, slates and ridges	Roof	N/A	N/A
Cross-bracing	Roof	N/A	! Reduces space available in attic for other structural/thermal functions
Hip-roof (with slopes of 30 °)	Roof	+ Heavy precipitation	N/A
Hurricane straps to fasten the roof to the walls	Roof	N/A	N/A
Lightning rods/air terminals	Roof	N/A	! Lightning rods have a voltage limit and sometimes cannot divert all the energy
Physical non-continuity between the roof of the building and an extension (covered terrace, veranda, patio)	Roof	N/A	N/A

Priority hazard: Storms

Solution	Element	Impact on other hazards	Key considerations
Short overhangs and protrusions	Roof	! Heat waves	! Reduces the amount of shade.
Sub-roofing and sheathing to reinforce the roof	Roof	+ Subsidence	N/A
Impact-resistant shingles	Roof & Preferred material	N/A	N/A
Favour hedges and shrubs over trees around the building	Vegetation	! Heat waves, + Subsidence	! Low profile vegetation will not create shade for the building ! Local species should be considered.
Plant dense vegetation in rows	Vegetation	N/A	N/A
Rainscreen cladding systems	Walls	N/A	N/A
Strong connections between exterior building elements (roof-walls, walls-foundations, foundations-ground)	Walls	N/A	! Could impact passive ventilation Retrofitting could be challenging
Secondary protection in walls for wind driven rain	Walls	+ Heavy precipitation	! May affect the quality of air and ventilation.
Sheathing to reinforce walls	Walls	N/A	! Assess impact on insulation.
Reinforcement and protection of openings, storm shutters	Walls & windows	+ Heat waves + Subsidence	N/A
Impact-resistant glass for windows and doors	Windows	+ Heavy precipitation	N/A
Sealant joint in windows to prevent moisture	Windows	+ Heavy precipitation	N/A
Storm hooks to secure openings	Windows	N/A	! Not a standalone solution
Installation of backup generators	Services	N/A	N/A
Protective device for surges	Services	N/A	N/A
Fix outdoor furniture and slabs to the ground	Space considerations	N/A	N/A

2.2.1. Building shape

The shape of a building should be carefully considered from the design stage to reduce the potential for storm damage. It is important to prioritise shapes that are less exposed to the wind and would reduce the risk of wind-related physical damage. For example, **aerodynamic shapes**, such as rounded corners or polygonal floor plans, limit wind resistance. The height of a building should not be more than twice as high as neighbouring buildings (Egli, 2007). During a storm event, surrounding vegetation may also be uprooted, impacting on buildings. Structures should be designed with sufficient robustness against tree strikes.

2.2.2. Foundations

To withstand high winds, a building should have its foundations adequately anchored to the ground. However, during certain types of storms, storm-driven water runoffs can create intermittent flooding and soil erosion, which will impact the foundations of a building. Structures in storm-prone areas should be designed with the **lowest liveable floor elevated above ground level**, with appropriately anchored foundations (see Section 4 on Flooding). However, this may have a negative impact on wind loads, therefore structures should be evaluated to provide the most appropriate storm mitigation solution. To prevent flooding in the basement, sump pumps can be installed (BrokerLink, 2021).

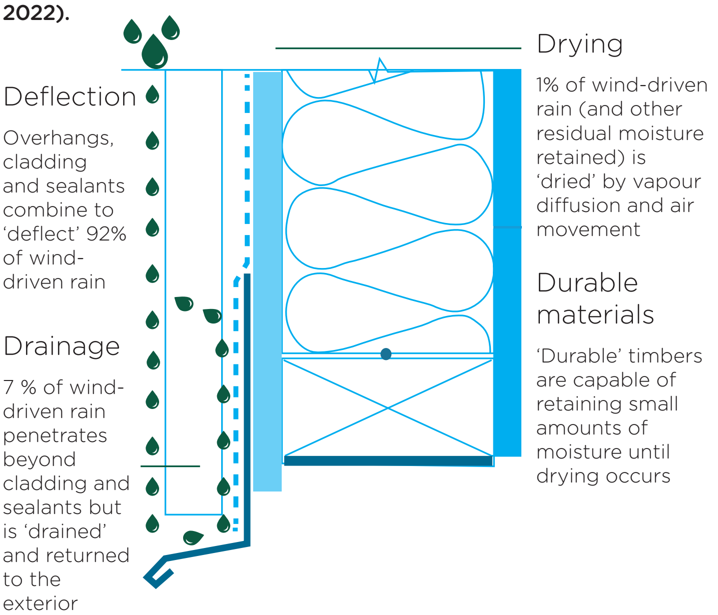
2.2.3. Walls

The design of walls, their architectural and structural details and overall connection to the stability structure in buildings is key for limiting the risk of storms in a building. At a system level, it is essential to have **strong connections** between the walls, the roof, the walls and the foundations.

External concrete and masonry walls should have coatings and water repellents applied to minimise the entry of moisture into the wall assembly and protect the wall from deterioration in areas experiencing frequent wind-driven rain (Trimber, 2016).

Timber constructions should have full structural sheathing of exterior walls. **A rainscreen design, or cladding**, with a secondary line of protection such as a **vapour barrier, and drainage system** is recommended to control moisture and facilitate water drainage (Figure 13).

Figure 13: Moisture barrier and drainage system protects walls against wind-driven rain, (adapted from Canadian Wood Council 2022).



Rainscreen cladding is a form of double-wall construction that uses an outer layer to keep out the rain and an inner layer to provide thermal insulation, prevent excessive air leakage and carry wind loading (Proteus Facades, n.d.). Section 3 provides further information on solutions for heavy precipitation.

Doors and other **openings should be reinforced** and protected with strong shutters. In addition, open surfaces should be limited in size.

2.2.4. Windows

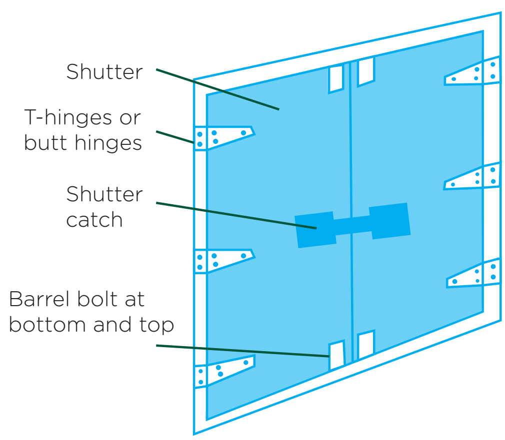
Any openings, including windows, should be appropriately designed to prevent any breakage that could let wind into the building, causing indoor wind pressure build-up that can potentially damage the structure (such as roof uplift). **Impact-resistant glass** should be used on windows and can either be introduced during the manufacturing process, or it may be added to existing windows with a film. To hurricane proof windows, a film of PVB (polyvinyl butyral) or EVA (ethylene-vinyl acetate) sandwiched between two layers of glass is the most common solution. PVB combined with a layer of PET (polyethylene terephthalate) makes for a solid glazing option (Rodriguez, 2021). Alternatively, a window safety film can keep the glass contained from shattering debris or the impact of hail (BrokerLink, 2021). The glazing thickness should also be considered. **Storm hooks** can be used as additional protection on windows.

It is possible to add an additional layer of protection outside windows. **Storm shutters** provide an efficient first line of defence against high winds and related projectiles whenever the design of the building allows it (see Figure 14). That said, shutters may not be technically feasible in high rise buildings.

In the case of heavy rain accompanied by high winds, windows must be designed and **appropriately sealed** to prevent moisture and water from entering the building. A secondary defence can be designed to intercept and drain water that penetrates the sealant joint. More information can be found in section 3 on Heavy Precipitation.

Historic windows should be repaired and maintained by skilled workers (instead of being replaced) to conserve their important contribution to the character of a building. Appropriate solutions may include: removing excess paint, inserting draught proofing, weather-stripping, replacing hinges and screws with stronger ones, and installing storm shutters (Historic England, 2020).

Figure 14: Shutters with hinges and bolts add an extra layer of protection on windows and doors



2.2.5. Roof

A building's roof can be wholly or partly uplifted from the building structure during high winds. To avoid this, simple improvements can be made, such as **changing the size and frequency of fastenings** for roof tiles, slates, and ridges. Screws and large washers are recommended for fastening, offering a cost- effective and straightforward solution that significantly improves wind resilience.

When designing the structure of a roof in storm-prone regions, two aspects should be considered: geometry and stability.

Roofs with multiple slopes perform better than roofs with only two slopes (gable roofs). Studies show that **hip-roofs** Figure 15) with slopes of 30° have the best results in resisting strong winds. Even and steep slopes also help shed snow most easily during blizzards and snowstorms (FEMA, 2014). If a chimney is installed, it should be straight through the roof ridge, or as close to the centre of the structure as possible (chimadmin, 2019). High winds can cause damage to chimneys in poor conditions. Chimney chases should be capped to prevent the generation of moisture (MCP Chimney Services, 2016). However, caps are subject to large wind forces and so must be attached firmly (Pickles, 2016). Refer to Section 3 on Heavy precipitation for more information.

Figure 15: Hip-roofs (left) are considered more resistant to strong winds than gable roofs (right)

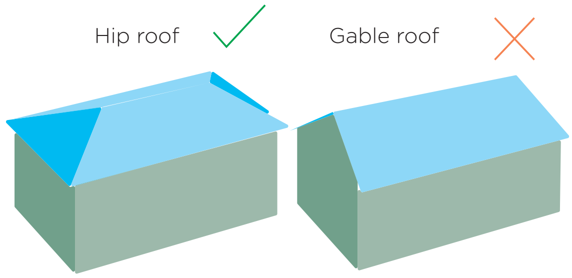
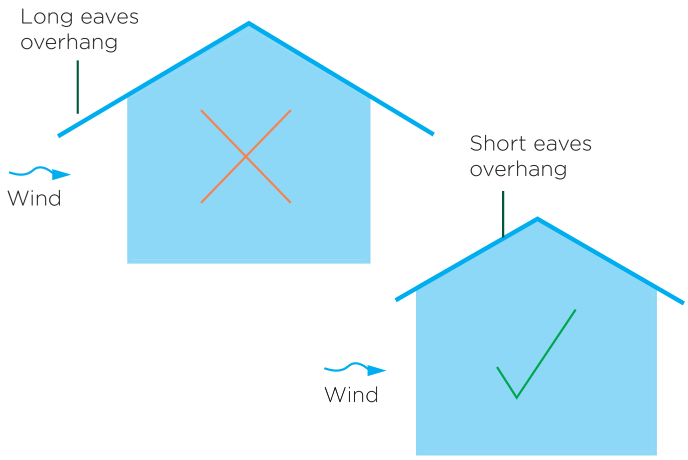


Figure 16: Long overhangs should be avoided to reduce wind loads on the roof (IFRC-SRU and Decoray, 2020)



Long overhangs or **any type of roof protrusion should be avoided** to reduce wind loads (Figure 16).

Structural elements can reinforce and support the roof from below, such **as cross- bracing** (Figure 17). The result is an X-shaped brace that provides stability to the structure and precludes the collapse of the roof due to winds.

Figure 17: Gable bracing provides additional stability to a roof (FEMA, 2022)

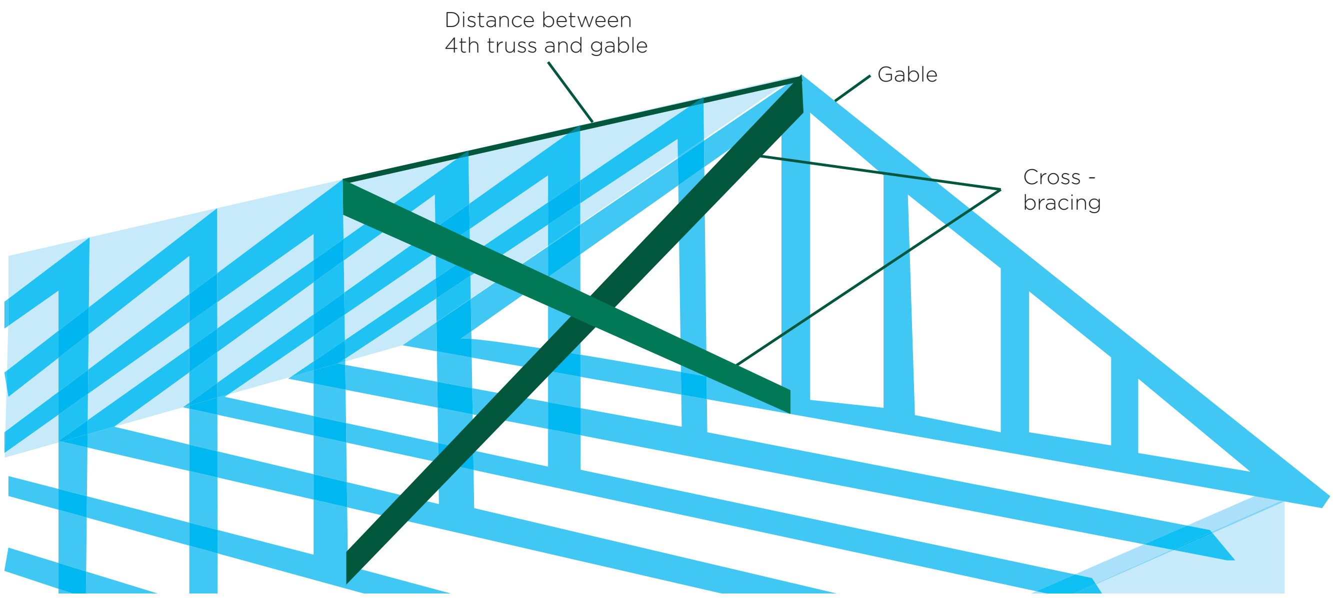
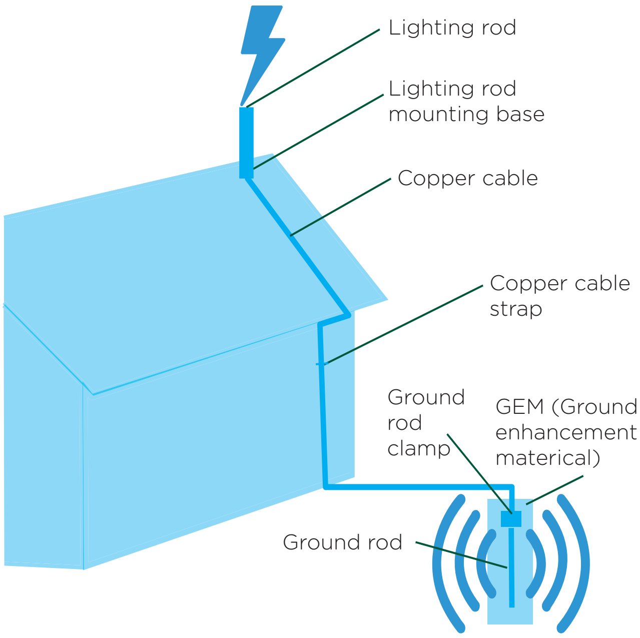


Figure 18: Lightning rods help redirect electrical currents to the ground



Sheathing a roof can provide a stiff diaphragm to help resist and distribute high wind loads. In the case of retrofitting a roof, reinforcing with sheathing from the attic floor to the wall and roof should be considered. Roof ventilation should be provided according to building codes.

The choice in envelope materials should be considered carefully within a storm hazard area. For example, damage can be significantly reduced during hailstorms by providing a **metal standing seam roof or impact resistant shingles** (Parker, 2022).

Thunderstorms involving lightning can cause fires and power surges. **Lightning rods** (Figure 18), or air terminals, are one way to redirect electrical currents to the ground (Edwards, 2021), although, lightning rods have a voltage limit and sometimes cannot divert all the energy.

Around the roof, insufficient roof drainage can lead to flooding and ice dams during storms involving rain or snow. **Effective drainage systems** should be implemented to prevent interior water leakages and mould growth, and concentrated snow load at the eaves.

Under the roof, the linkage between the roof and the walls should be reinforced to prevent uplift. For instance, **hurricane straps and clips** (Figure 19) help fasten the roof to the walls of a building in case of high winds.

Other types of roofs such as a covered terrace, veranda and patio should also be considered. In this case, it is recommended to have a physical non-continuity between the main roof of the building (Figure 20) and the roof of a veranda, patio or covered terrace. This will prevent damage to the main roof if the extension is carried away.

Figure 19: Hurricane straps offer a strong junction between the roof and the walls but can also strengthen other connections

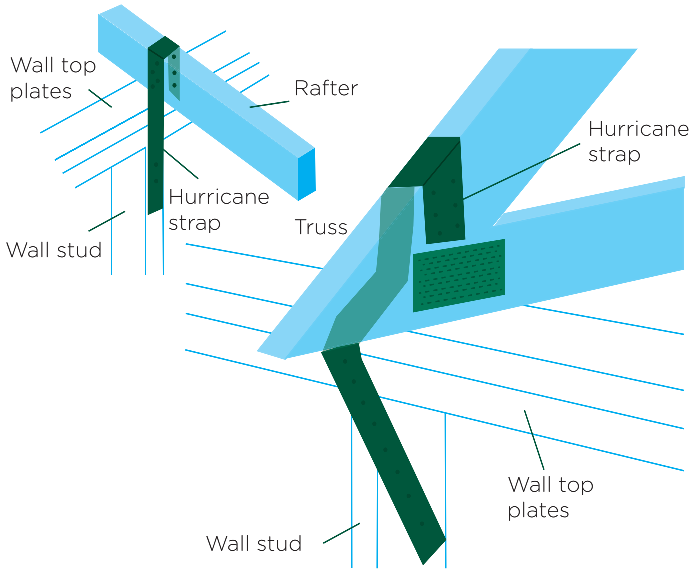
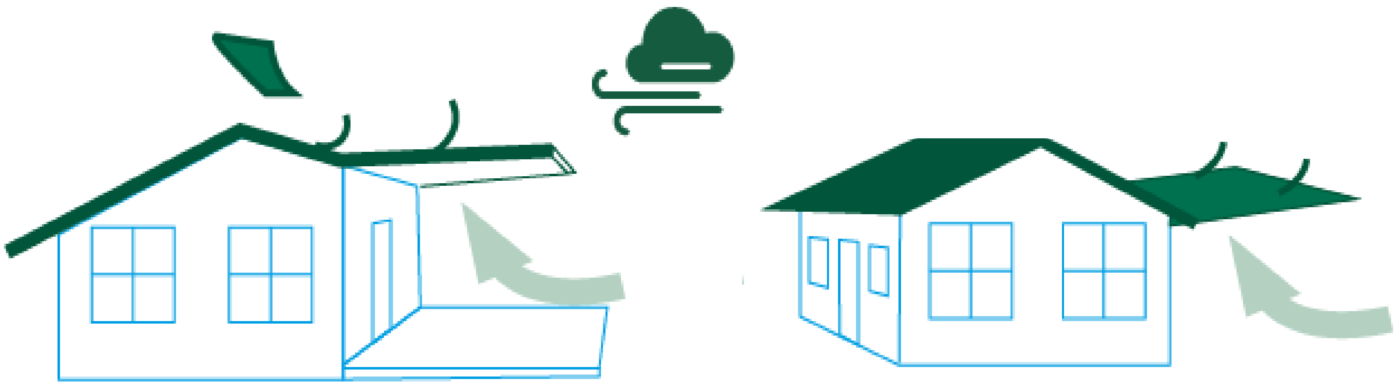


Figure 20: Triggers points of separation between a roof and a veranda, patio or covered terrace.



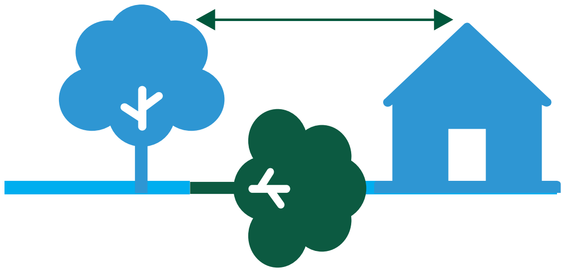
Canopy built in to main roof: to be avoided

Canopy separated from to main roof: damage is isolated

2.2.6. Vegetation

Placing **vegetation around a building** acts as a windbreak and limits the power of the wind by offering some level of protection in the event of storms. This will also help prevent damage to heritage sites from wind erosion (Wang et al., 2019). It is recommended to **plant dense vegetation in rows** to increase the effect of a windbreak. Surrounding vegetation, specifically trees, should always be well maintained and checked for weakness, decay or disease to avoid falling onto the building or property and causing damage (Figure 21). Therefore, it may be best to **favour hedges and shrubs over trees**.In addition, trees may be hit by lightning during a thunderstorm, so it is best to keep the number of trees near a building to a minimum (State Farm Mutual Automobile Insurance Company, 2022).

Figure 21: Trees should be well-maintained and kept at a safe distance from the building. Strong winds may cause trees to fall.



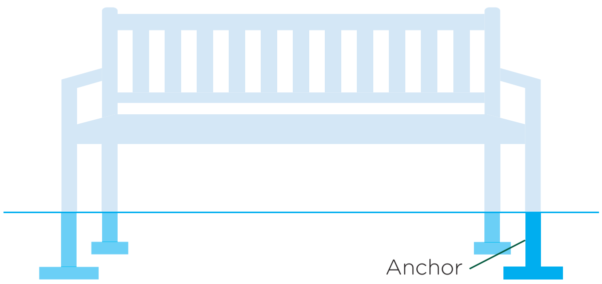
Green roofs, rain gardens and bioswales help reduce stormwater runoff generated during severe storms and after winter storms with melting snow. Research has shown that green roofs can be designed to withstand Category IV hurricane strength lateral winds without damaging or displacing any of the components (Morris, 2021). More information on green roofs is available in Section 1 and Section 3.

2.2.7. Preferred materials

Roof materials will impact the structure's ability to resist damage from storms, including high winds and hail. **Impact-resistant shingles** can be installed to withstand high winds and hail damage. During snowstorms and blizzards, snow needs to be able to slide off the roof easily to avoid creating unbalanced snow loading. Therefore, slippery surfaces are preferred in snowstorms and blizzards-prone regions (Massie, 2015). **Steel deck roofs, hefty gauge metal**, and **standing seam roofs** typically perform best overall. Slippery surfaces such as metal panels or single-ply membrane roofing will also help snow slide off the roof to avoid snow loading. Cool metal roofs have coatings specifically designed to reflect the sun's energy and reduce the amount of heat absorbed into the building (Calapa, 2022).

If there are solar panels on the roof, they should be **impact resistant** or protected by a hard shell or padded cover, which may impact their performance.

Figure 22: Bench anchored to the ground to avoid being swept away by strong winds



2.2.8. Space consideration

Outdoor equipment can be swept away during violent wind episodes causing severe human, animal, and material damage. Furniture can be **mechanically fixed** to the ground **with a ground anchor** (Figure 22). Fences should be of a wind-resistant design and the posts supporting them should be strong. Slab terraces can also be subject to considerable uplift forces and should consequently be fixed down to prevent uplift.

2.2.9. Primary structure

The stability of a structure can be affected by storms through high wind loads, moisture and precipitation. The design of the external envelope, the architectural and structural details and overall connection to the stability structure in a building is key for adapting to storm risk. At a system level, it is essential to have **strong connections** between the different structural elements (walls, roof and foundations). All structures require **adequate detailing** of **connections** to **account** for **shear** and **uplift forces**, accounting for expected increased wind levels.

Wind load conditions can be accounted for, by undertaking **performance-based wind design (PBWD)**. For areas experiencing extreme wind conditions, meteorological data can be combined with reanalysis data, to provide a more accurate approach to the design of wind loads.

Although existing structures may have a degree of redundancy to allow for alternative load paths, the anticipated increase in severe storm events across Europe may expose existing buildings to increased wind loads. An **assessment** by an engineering professional is required to determine whether any **structural strengthening** may be required.

2.2.10. Services

Sites should be carefully designed to protect themselves against high-wind related power outages by, for example, **installing backup generators** and **burying distribution lines**. IIf there are photovoltaic panels or other sources of energy on-site, storms can damage these. During thunderstorms and lightning strikes, damage can also be caused to electronic devices, in addition to causing a power surge. Installing **surge protective devices** can prevent this (Edwards, 2021). In rooms with a strong internal moisture load, HVAC systems should achieve proper building pressurisation and fully dehumidify the air that flows across the cooling coil (MacPhaul and Etter, 2016). Refer to Section 3 on heavy precipitation for more information.

2.3 Technical assessments, guidance & tools

The United States Federal Alliance for Safe Homes' Resilient Design Guide on High Wind Wood Frame Construction provides architects, designers and homeowners with detailed technical information to make a construction resilient to the wind. Types and measurements of equipment are detailed in this guide.

FEMA's Design Guide for Improving Critical Facility Safety from Flooding and High Wind includes a comprehensive guide with design features and building materials recommendations for design teams and local authorities to adapt to strong winds and wind-driven rain, dust, snow, debris, etc.

L'Observatoire de l'immobilier Durable's guidance on Climate Adaptation Response in Buildings is a guide that tackles heat waves, droughts, flooding, marine submersion, storms and wildfire. It includes high-level technical recommendations, barriers/levers, and the skills levels and approximate cost needed (in French).

Climate Resilience Strategies for Buildings in New York State provides an extensive guide on resilience strategies. Solutions are structured by location, hazards (hurricanes/tropical storms, flooding, severe storms, wildfires, heat waves, pest infestation), and industry actors. Each solution includes a case study.

The city of Brussels has produced a guide on wind management approaches for buildings: 'Le Guide du Bâtiment Durable. Implantation et forme des bâtiments: quels choix influencent les effets du vent?'. The Guide Bâtiment Durable: Matériaux also provides support regarding the choice of materials.

UNEP's A Practical Guide to Climate-resilient Buildings & Communities is an exhaustive guide providing support for improving the built environment and providing safety against climate change-related hazards. This guide tackles drought, flooding, rising sea-levels, heat waves, and cyclones and strong winds.

Interreg Central Baltic & European Union's Integrated Stormwater Management Toolbox provides a matrix of resources, including strategic approaches, planning tools and programmes, design solutions, and assessment tools to manage storm water in urban areas.

New York Urban Green Council's Building Resiliency Task Force is a simple short report combining findings from real estate owners, property managers, architects, engineers, contractors, utility representatives, subject matter specialists, cost estimators and attorneys.

Risks related to high winds, hail, rainfall and snow alongside recommendations can be found in this Swiss guide: Protection des objets contre les dangers naturels météorologiques, Établissements cantonaux d'assurance.

The US Federal Emergency Management Agency (FEMA) Avoiding Hurricane Damage: A Checklist for Homeowners is a short document to support homeowners in implementing necessary steps to secure their homes. This checklist is structured in a Q&A format.

FEMA's Protect Your Property from High Winds provides valuable information for homeowners to prepare their homes in the event of a storm.

UNDP's Cyclone resistant building architecture is a practical and technical guidance that explains the physical effects of cyclones on buildings and provides design solutions in detail.

2.4 Case studies

In 2000, a development called **Arverne by the Sea**, located in the Rockaway Peninsula within the borough of Queens in the city of New York was **designed** to **withhold rising sea-levels** and **hurricanes**. Buildings were built at angles from the beach to lower the wind's pressure. To strengthen the foundations against storms, deep timber piles (6-7 metres below grade) reinforced wtih concrete and steel were used. To avoid damage from storm surges and sea-level rise, the site was raised by an average of 2.5 metres, raising most of the site well above the 100-year floodplain. Steel frame construction was used for the buildings. The single-hung windows were pressure-resistant and well-sealed to prevent water infiltration. Roofs were secured with wind-resistant shingles and with a high-wind-proof nailing pattern. The front and rear gardens of each property as well as the streets were equipped with storm drains that connected to an underground drainage system. As extreme storms can cause power outages, the development buried electrical cables underground and installed an energy vault (Schwanke, 2014).

These solutions have proven effective as the development resisted Hurricane Sandy in 2012.

Aerodynamic shapes have been used in many countries, especially in tall buildings, such as in London, in the United Kingdom. A guide for wind microclimate conditions has been produced by the City of London.

The City of Toronto reacted to its vulnerability to severe storms and winter storms by creating its **Wet Weather Flow Management Guidelines** document, which includes roof drainage systems – see Section 3 and Section 4 for further guidance on heavy precipitation and flooding (Rajkovich et al., 2018).

2.5 Industry actors

2.5.1. Government, regulators & local authorities

Policymakers and planners need to understand the local risks and impacts of storms to incorporate resilience into national and local hazard adaptation plans. They should **guide preparation** and **response efforts**, and **guide design teams** on the prevention of rainfall penetration, pressure build-up that leads to roof uplift, and windborne debris (Rajkovich et al., 2018). One example would be through **Eurocodes** which provide a regulatory basis for the design of buildings in Europe, together with other civil engineering works and construction products. However, additional regulation and guidance is needed to capture all the parts of buildings.

Health and safety are key concerns in the event of natural disasters. Authorities should make sure that buildings **meet safety requirements through inspection**. Defective elements should be renovated if necessary. **Governmental policies, regulations** and **tools** should be **publicly available,** to support design teams and provide a valuable and reliable source of compliance (Swanson et al., 2021).

Planning processes should incorporate climate hazard assessments and measures to prevent damage within the early stages of planned developments. Planners should make sure that, for instance, groups of buildings are not constructed in rows in order to **avoid wind tunnels**. Policies should be developed to mandate or encourage the **implementation of alternative energy sources** to **support critical facilities**, such as hospitals, to ensure they can remain operational during storm events. In addition, planners should **review opportunities** to **install microgrids** and **bury distribution power lines** to provide communities with secondary energy sources if central grids fail (Swanson et al., 2021).

2.5.2. Investors, developers & insurance providers

Investors, developers and insurance providers should be aware of the climate history and future forecast of a region to **assess risks** accordingly. When evaluating a site or potential developments, wind tunnel and wind pressure effects should be considered. Areas near to water bodies, mudflats, salt flats or unbroken ice should receive greater evaluation as flat surfaces increase wind pressure (FEMA, 2007).

Additional **risk assessments** and **modelling** should be undertaken for **tall buildings**, as they will be more vulnerable to stronger winds (Assurance Prevention, 2021).

The public realm and landscaping design around the building should also be considered for storm implications. **Building certifications** such as **BREEAM** and **LEED** can provide good reference material for consideration. Also, reporting frameworks such as **EU LEVEL(s)** provide an understanding of actual building performance.

2.5.3. Design teams (engineering and architecture)

A list of technical solutions that design teams can implement to increase the resilience of buildings to storms from the design stage is provided in Section 2.2. Building professionals should formulate a **preparedness** and **response mechanism** according to a specific area's past, current and future wind patterns, to inform building design. Local professionals should also consider gathering information after critical hazard events to develop a **localised database** on how **building performance could be enhanced** (Rajkovich et al., 2018). For existing buildings, design teams should **calculate** the **wind loads** to upgrade the load resistance of the envelope and structure. A **site investigation** should be done to check the deterioration of primary elements and ensure that existing drawings are accurate (FEMA, 2007). Overall, a record of calculations and tests must prove that: a building is strong enough to resist wind loads; ice build-up and strong winds do not cause damage to power lines and utility poles; essential infrastructure is not at risk from falling tree damage; increased amounts of dirt, dust and snow do not impair the population's health and safety (Swanson et al., 2021).

2.5.4. Building users, facility managers and owners

Building managers and owners can implement many of the technical solutions listed in Section 2.3 to assess and improve a building's protection from high winds.

Building users should be aware of **extreme storm event response protocols** and make sure that **evacuation routes** are free to ensure effective emergency management when necessary (Rajkovich et al., 2018). All **outdoor equipment** susceptible to flying away and becoming projectiles should be safely **stored away** or **fixed to the ground**.

Building users and facility managers should ensure building **openings** are **sealed**, **blocked** and **reinforced** during a storm event to prevent them from opening violently or flying away. Ensuring the building is sealed during a storm is particularly important, as strong gusts of air can (in extreme situations) lead to a build-up of internal pressure, pushing the roof from below and the side and rear walls outwards (FEMA, 2007).

3. Heavy precipitation

3. Heavy precipitation

3.1 Description

Heavy precipitation includes extreme rainfall, snow and hail. Extreme precipitation events will increase in intensity and duration as a result of climate change. The classification of heavy rainfall depends on the amount of rainfall and the likelihood of it happening over time. Higher projected temperatures and warmer oceans increase the amount of moisture in the air; the warmer the air, the more evaporation there is, inducing events of more frequent and heavier precipitation (US EPA, 2016).

The impact of heavy precipitation will depend on the duration and type of precipitation in combination with the features of the land, such as slopes and the permeability of surfaces. Extreme precipitation can cause direct damage to buildings, whether snow, hail or rainfall, impacting the roofs of buildings most directly.

Increased urbanisation, as foreseen in Europe, can enhance the risk on pluvial flooding in cities (Kaspersen et al., 2017). Impermeable tarmac streets prevent water from infiltrating into the grounds, and drainage systems are often not dimensioned to meet the demand of both an expanding city and an increase in heavy rainfall. Prolonged heavy rainfall can also cause pluvial flooding, leading to damage inside buildings. For more detail, see Section 4 on flooding, where solutions to increase building resilience to heavy rainfall are also described. These can also contribute to preventing pluvial flooding.

3.2 Solutions

Solution	Element	Impact on other hazards	Key considerations
Avoid square and rectangular flat surfaces perpendicular to the wind	Building shape	N/A	Not suitable for a retrofit or renovation
Green facades	Walls	+ Heat waves	+ Benefits for biodiversity + Reduced energy demand
Rainscreen or cladding system	Walls	+ Storms	N/A
Water-repellent materials	Walls & preferred materials	+ Storms	! Changes in breathability to the structure need to be assessed
4mm thick tempered glass panes	Windows	+ Storms	N/A
Effective sealant	Windows	+ Storms + Flooding	N/A
Hail proof blinds and shutters	Windows	+ Storms	N/A
Secure loose joints by cramping, gluing, re-wedging and pinning	Windows	+ Storms + Flooding	N/A
Infiltration trenches	Preferred materials	! Flooding + Storms	N/A
Metal for roofing	Preferred materials & roof	! Flooding + Storms	! The embodied carbon should be considered against other options
Passive landslide control measures	Primary structure	! Flooding + Storms + Landslide	N/A
Hail net	Roof	+ Storms	N/A
Heat tracing in gutters	Roof	+ Drought + Storms	! Requires heat/energy source
Inspection and cleaning of the roof drain, gutters and downspouts, and snow	Roof	+ Storms	N/A
Warm roof	Roof	+ Heat waves	+ Reduces energy demand
Inverted roof	Roof	+ Heat waves	+ Reduces energy demand
Pitched roofs	Roof	+ Storms	! Cannot be used for intensive green roof

Priority hazard: Heavy precipitation

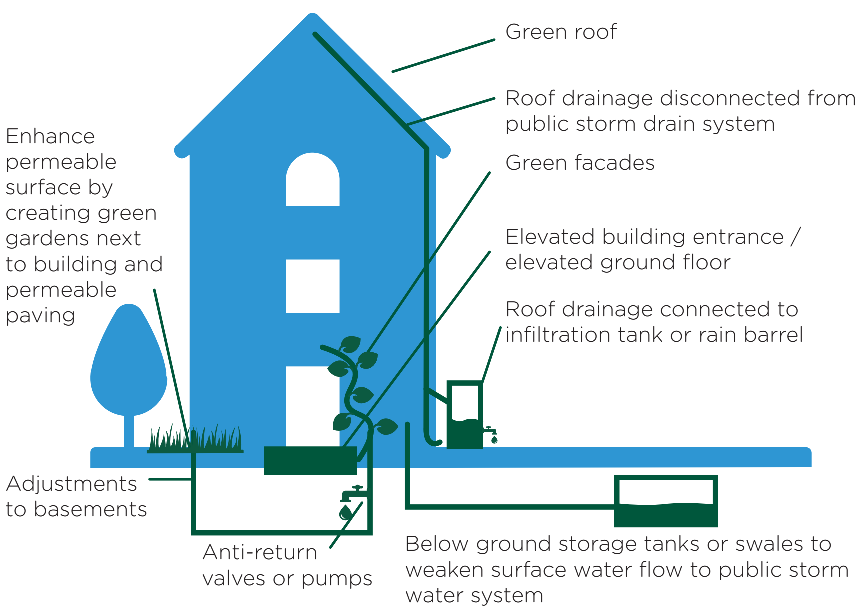
Solution	Element	Impact on other hazards	Key considerations
Truncating downspouts	Roof	+ Flooding + Drought	! Not a standalone solution
Blue roof	Roof & vegetation	+ Heat waves + Drought + Flooding	+ Reduces energy demand
Blue-green roof	Roof & vegetation	+ Heat waves + Drought + Flooding	+ Benefits for biodiversity + Reduces energy demand
Green roof (extensive or intensive)	Roof & vegetation	+ Drought + Heat waves + Storms + Flooding	+ Benefits for biodiversity + Reduces energy demand
Permeable or pervious soils	Vegetation & space considerations	+ Flooding + Storms + Heat waves ! Subsidence	N/A
Rain gardens and swales	Vegetation & space consideration	+ Drought + Heat waves + Storms	+ Benefits for biodiversity + Can be combined with rainwater harvesting
Ground preparation	Structure	+ Flooding + Storms + Drought	+ Improves drainage + Mitigates landslide risk Retrofitting could be challenging
Anti-return valves for toilets and sinks / sewage pumps	Services	+ Flooding + Storms + Drought	N/A
Disconnect surface water from sewage	Services	+ Flooding	N/A
Drainage network dimensioned to future runoff projections	Services	+ Flooding	N/A
Placement of sinks at a minimum height	Services	+ Flooding + Storms	N/A
Rainwater tanks	Services	+ Drought + Flooding + Storms	N/A
Sustainable urban drainage systems (SuDS)	Services & vegetation	+ Flooding	+ Natural filtration of pollutants

When designing solutions, it is important to consider the uncertainty of future scenarios of heavy precipitation due to climate change when choosing and putting solutions into practice.

For example, water storage needs to be dimensioned to respond to higher demand periods, but should also be resilient to droughts (thus preventing evaporation), and account for future extreme changes in rainfall patterns

Various building solutions can be applied to adapt to the impact of heavy precipitation as illustrated in Figure 23.

Figure 23: Overview of solutions to heavy precipitation for buildings



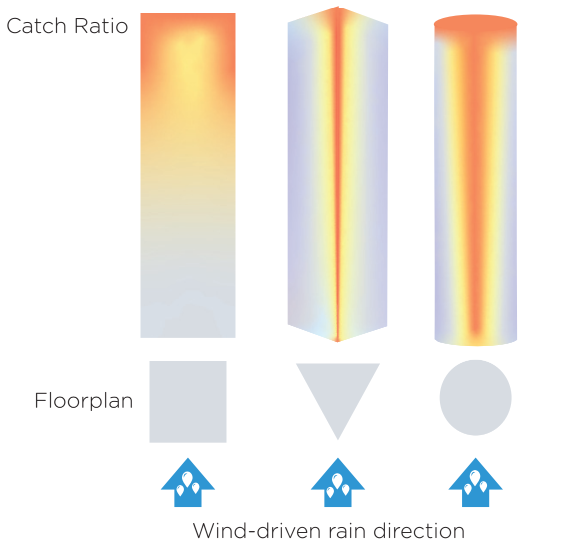
3.2.1. Building shape

Climate change may increase rainfall and wind speeds leading to increased incidences of wind- driven rain. Under the effect of wind, rain droplets are carried with horizontal momentum and accumulate on windward surfaces of buildings. Wind-induced pressure can then drive the rainwater through cracks and pores leading to water penetration, cladding damage and degraded hygrothermal performance (Abu-Zidan, Nguyen and Mendis, 2021).

Triangular-shaped buildings with edges to the wind will have a breaking effect on horizontal rainfall intensity. Flat surfaces perpendicular to the wind receive more intense wind-driven rain, especially at the top corners.

Shapes with a higher curvature experience intense horizontal rainfall on a smaller surface in the centre of the windward face of the building (see Figure 24). **Square and rectangular buildings with flat surfaces perpendicular to the wind are the most vulnerable** to intense wind-driven rain (Abu-Zidan, Nguyen and Mendis, 2021), and thus may require **sheltering**.

Figure 24: Catch ratio distributions on windward surfaces, based on three building shapes (Figure adapted from: Abu-Zidan, Nguyen and Mendis, 2021). Colours indicate where the building is most hit by the wind-driven rain.



3.2.2. Foundations

Heavy precipitation can cause flooding damage. Solutions such as **elevated foundations**, and **wet** and **dry-proofing basements** are covered in section 4 on flooding.

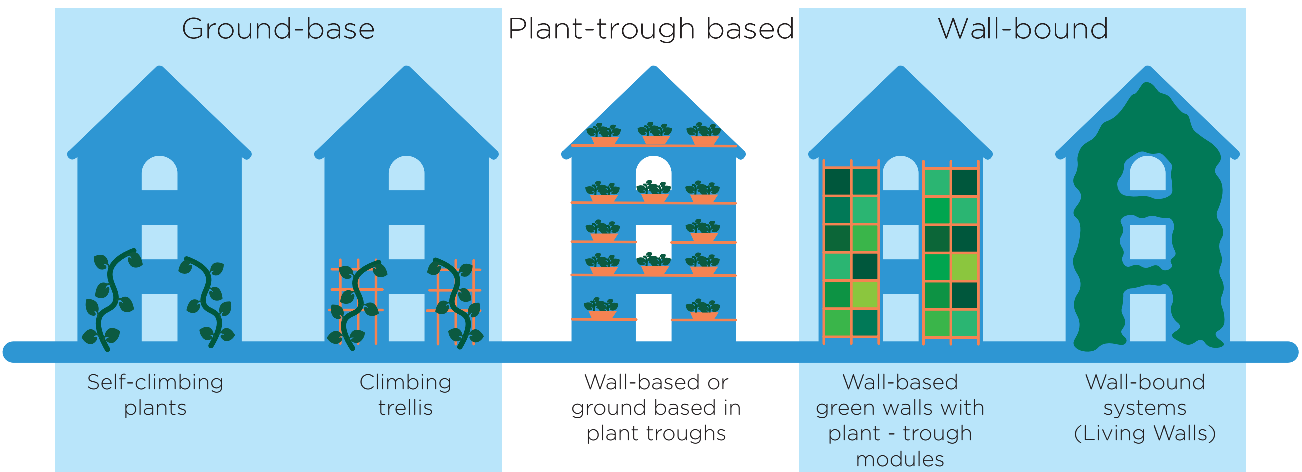
Various adaptations to a building's foundations can be implemented to mitigate precipitation-induced landslides. Adequate **ground preparation** iis necessary to ensure foundations will not become displaced in the event of heavy precipitation. Landslide mitigation measures include soil strengthening, erosion control measures (geotextiles, rip rap) or a modification to the slope geometry to improve slope stability (infilling, stem and gabion walls).

3.2.3. Walls

Plants on a **green facade** can act as a rainscreen and help decrease air and surface temperatures by canopy evapotranspiration and shading. There are several ways to construct a green facade (Pearlmutter et al., 2021): (see Figure 25)

- Ground-based green facades: evergreen or deciduous climbers grow on the wall, rooted in the soil next to the facade. The self-clinging plants climb up the wall as they grow, either directly on the wall, or on a frame connected to the wall;
- Green facades with no roots in the ground: the plants grow on special thin layers of substrates to reduce the weight of the green facade. This option is more expensive, requires more maintenance and provides less water retention than the ground-based facade.

Figure 25: Different types of green facades



Priority hazard: Heavy precipitation

Climate change is expected to increase the amount of wind-driven rain which can cause damage to interior walls and dampen materials, specifically where there are poor construction building details or cracks and cavities in the outer wall. In most European climates, solar radiation is sufficient to dry walls, even for walls with retrofitted interior insulation (Bottino-Leone, 2020). The application of **water-repellent materials** on the walls, or their use as a building material for walls, is a good way to reduce the impact of heavy rainfall. More information on these can be found in the preferred materials section. However, the effectiveness of a water-repellent coating was found to be uncertain in Sweden (Olsson, 2017).

An outside barrier can be a first line of defence, such as a rain-screen design or cladding. **Screened-drained walls** or **rainscreen cladding systems** assume some rainwater will penetrate the outer surface of a wall and remove this water by designing a **drainage system within the wall** (Straube, 2011). A cladding material is fixed to the building via a supporting structure. This protects an insulation layer on a bearing wall. This combination controls moisture and facilitates water drainage in areas experiencing frequent wind-driven rain. To protect against hail, several materials can be used on walls. These include **sandwich panels, profile sheets, thin sheets** and **fibre cement panels**. It is also important to consider opportunities to ensure the cladding or screen functions as more than just a rain screen; design and materials may enable it to resist wind, snow, solar radiation, impact and flame spread (Straube, 2011).

In most historic buildings, permeable materials tend to absorb more moisture, which is then released by internal and external evaporation. These buildings are often referred to as 'breathing' buildings. If properly maintained, the permeable materials used in the building (such as lime and/or earth-based mortars, renders, plaster and limewash) can act as a buffer for environmental moisture, absorbing it from the air when humidity is high, and releasing it when the air is dry (Historic England, 2016),

Overall, building maintenance and repair is an effective first step to prevent damage from wind-driven rain.

3.2.4. Windows

Heavy precipitation, especially hailstones, can cause damage to windows. Standard **4 mm tempered glass panes** used for multi-pane insulating glazing have a hail resistance of 3, meaning a 3 cm hail stone will not cause any damage to the window (Zhejiang Flat Glass CO., n.d.). Space between the window frame and the wall should be avoided, for these provide passages for wind driven rain. Ensuring **good sealing** requires special attention during the construction of the windows in the wall.

In historic buildings, decay in timber windows resulting from moisture penetration can be prevented through painting, regular maintenance and repairs. **Loose joints should be re-secured by cramping, gluing, re-wedging and pinning**. Decayed joints should be taken apart and defective members repaired by piecing-in. New timber and as much of the existing wood as possible should be treated with a solvent-borne preservative before fitting (Pickles, McCaig and Wood, 2017). Historic England provides a useful guide to restoringe traditional windows: Traditional Windows Their Care, Repair and Upgrading.

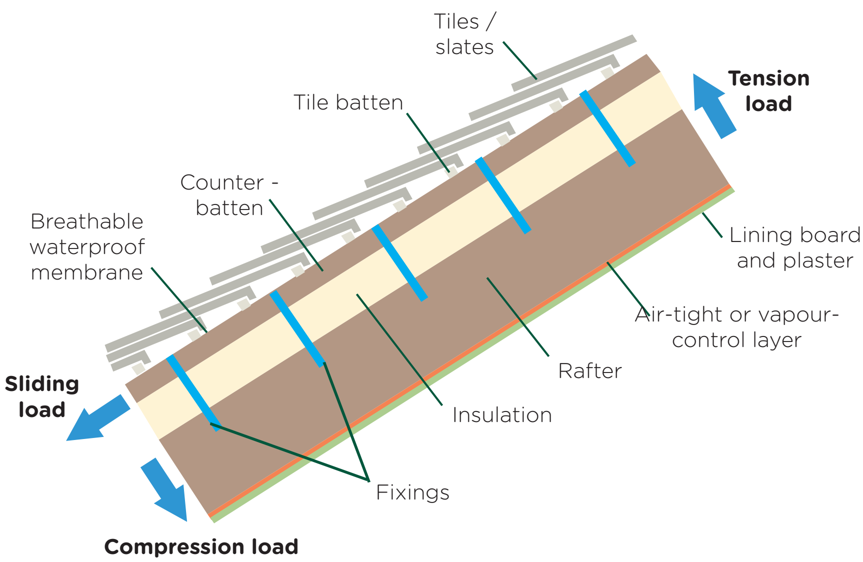
In high-risk hail regions glazing can also be protected by **hail-proof blinds** and **shutters**.

3.2.5. Roof

A **warm roof**, constructed with an insulation layer above the rafters, allows heat to be conserved within a property. A breathable waterproof membrane under the tiles/slates allows moisture to escape, which can prevent damp and associated mould problems. A **pitched warm roof** is considered to be the best for heavy precipitation, as the slope also offers protection from water pooling and infiltration.

However, technical challenges such as the structural load on a pitched roof, the thickness of the counter batten, the weight of the roof covering (Figure 26) need to be considered by engineering professionals (Helifix, 2012).

Figure 26: Pitched Warm Roof



An **inverted roof**, with insulation placed over the waterproof covering, provides similar protection but is more suitable for flat roofs (Gutter Maintenance, 2018).

In climatic zones with significant snow fall, roofs need to be designed to withstand expected snow loads. **Regular removal of snow** from roofs can also prevent property damage from excess weight on the roof, plus infiltration from snow melt. **Truncating downspouts** above ground level can ensure a free flow of water and prevent freezing at the bottom. **Heat tracing** iin gutters and downspouts can be considered a prevention to ice forming.

Gutters should be regularly maintained to ensure that they efficiently carry water away from the roof. They should be appropriately sized to carry volumes resulting from short durations of intense heavy precipitation. Th **inspection** and **cleaning of roof drains, gutters** and **downspouts** reduces the risk of blockages and ensures that water can flow freely through the drainage system (Aviva Insurance Limited, 2021).

Fragile elements of roofs, such as tiles or PV panels within the envelope, should be considered for protection with a hail net (Association des établissements cantonaux d'assurance incendie et infomaison, 2022).

Green roofs are adaptive to heavy rainfall and provide protection against heat waves. This is particularly true for green roofs equipped with a water storage capacity that allow high evaporation rates and prevent dry-outs. Green roofs can also increase the energy performance of a building, as studies show there is a lower heat loss in winter and better cooling in summer compared to an asphalt roof (Bekker et. al., 2011; Tam et al., 2016).

- **Extensive or standard green roofs** are green roofs with a relatively thin layer of substrate and vegetation (see Figure 27). Suitable vegetation types are sedum (a succulent) or for shaded roofs a mix of mosses and herbal plants. Sedum has a high-water storing capacity. Depending on the substrate, sedum roofs can retain rainfall depths up to 10 mm (Stovin et al., 2015). PV panels can be integrated into the green roof layers (with ballasted installation mechanisms), lowering the temperature and increasing the efficiency of the panels. Due to the relatively light weight of sedum roofs these can often be placed on existing roofs, up to an angle of approximately 35 °
- **Intensive green roofs** have a thicker substrate and plant layer, and a higher variety of plants sometimes including bushes, small trees and nesting places for birds and bats. Besides accommodating rainfall, intensive roofs, if designed accordingly, can contribute to an increase in biodiversity. This option often requires regular maintenance, depending on the type of vegetation. The choice in vegetation should be made in accordance with the roof strength and local environment (Meristem Design Ltd. 2022).

Figure 27: Example of extensive to intensive green roofs and their characteristics

Extensive	Semi-intensive	Intensive
Height: 6-20cm	**Height:** 12-25cm	**Height:** 15cm > 1m
Weight: 30-150 kg/m	**Weight:** 120-200kg/m	**Weight:** 180-500kg/m
Vegetation: mosses, sedums, herbs & grasses	**Vegetation:** grasses, herbs and shrubs	**Vegetation:** Lawn, perennials, shrubs & small trees
Cost: low	**Cost:** middle	**Cost:** high
Maintenance: low	**Maintenance:** periodically	**Maintenance:** regulary

Blue-green roofs are green roofs with a water retention layer underneath the green layer. (see Figure 28) Due to this reservoir, blue-green roofs have a higher water storage capacity than regular green roofs (Busker, 2022). The reservoir serves as a watering system in times of drought through a water capillary system. An automated valve is used to regulate the water level of the system. The watering system prevents the need for irrigation, which is often required for a regular intensive green roof.

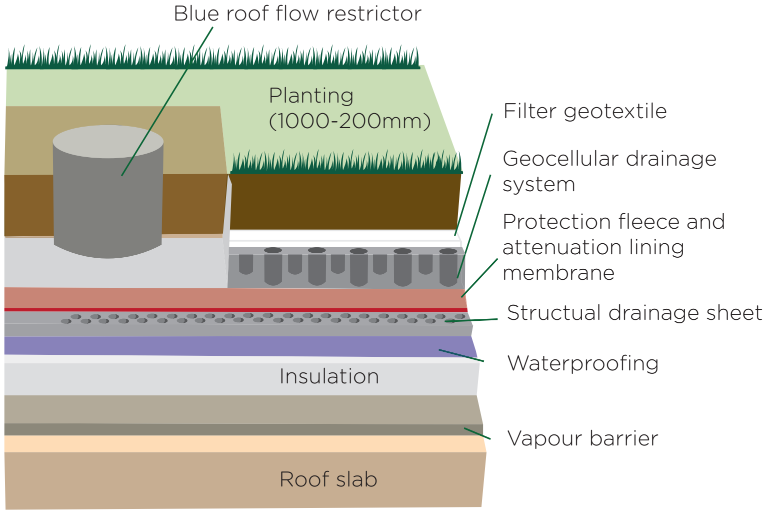
In addition, blue-green roofs show higher evapotranspiration rates on hot summer days compared to green roofs, contributing to cooling. Blue-green roofs are also heavy, so the roof structure should be able to support this weight (Busker et al., 2021).

Finally, **water roofs or blue roofs** are a way to temporarily store water on flat roofs during heavy rainfall. However the storage capacity depends on the construction of the roof.

A storage height of around 10 cm can be achieved for roofs with a maximum load of 1 kN/m2. During heat waves, a water roof provides only a very short-term cooling effect, as the water evaporates within days (NFRC, n.d.).

Glass roofs can be damaged by hail thus it is recommended not to use such roofs in high-risk hail regions. Alternatively, the glass should be strengthened or replaced with impact-resistant materials.

Figure 28: A blue-green roof system ensures that a flat roof can drain quickly in extreme weather events and slowly in normal use (ACO Group, n.d.).



3.2.6. Vegetation

Due to its absorbent property, vegetation can be used to mitigate for heavy precipitation events.

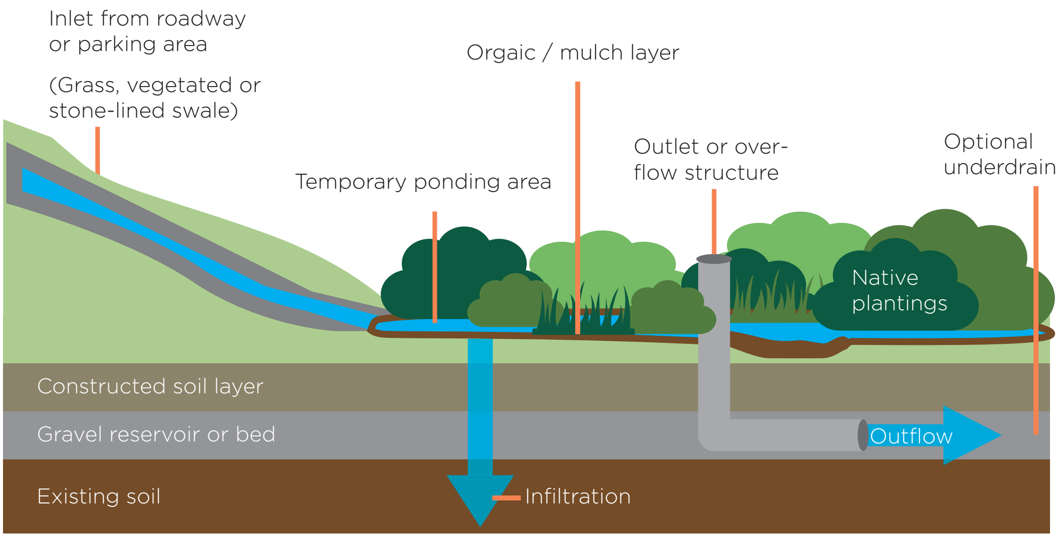
As mentioned above, green facades and roofs are natural solutions to retain a certain percentage of rainfall. These solutions are part of what is called **sustainable drainage systems (SuDS)**. Other types of SuDS can be integrated into the landscaping such as **swales, rain gardens and bio-retention areas** (see Figure 28). Swales are vegetated channels that promote infiltration where soil and groundwater conditions allow (OIE, 2013).

They should be engineered as part of a landscaping strategy and placed at an appropriate distance from the building. Rain gardens are an infiltration method that increases the amount of water entering the soil and, in turn, reduces the rates of runoff and volumes of surface water.

Figure 29: Permeable, vegetation-based tiles for driveways

Rain gardens can be combined with rainwater harvesting measures (Newground, 2021). **Permeable, or pervious, surfaces** are another form of SuDS that allow infiltration through gaps and voids in the surfacing. Permeable surfaces can be applied anywhere around the building but are usually used in driveways and parking areas (SusDrain, 2022a).

Figure 30: Bioretention areas rely on engineered soils, enhanced vegetation and filtration to remove pollution and reduce runoff downstream (SusDrain, 2022b). Diagram adapted from Massachusetts Department of Environmental Protection (MassDEP, 2005).



3.2.7. Preferred materials

Exterior building walls can be protected against heavy rainfall with the use of water-repellent materials. These are different to waterproof materials, which are described in the Flooding Section, and can be more easily combined with climate mitigation measures such as insulation.

Examples of water repellent building materials include:

- tiles with water-repellent setting mortar;
- double-leaf facing masonry with an air layer and thermal insulation;
- rear-ventilated exterior wall cladding;
- walls with external insulation;
- exterior timber walls with weather protection.

Hail, depending on the size, can cause damage to different types of material on both roofs and walls, so the material choice should be robust. Repairing damage shortly after a hailstorm can prevent further harm. In hail-prone regions, **metal deck sheets** on roofs can provide an effective protective material. While hailstones can dent the metal sheets, damage is often superficial as they are not penetrated easily.

3.2.8. Space consideration

The space around the building provides opportunities for adaptation against heavy precipitation.

The concept of sponge cities can provide a series of recommendations to harness nature and space to absorb rain and prevent flooding (World Future Council, 2016). These include continuous open green spaces or bio-swales, porous roads and pavements that can naturally detain and filter water.

In hail-prone regions, outdoor equipment should be designed to resist the impact energy of hailstones.

3.2.9. Primary structure

Heavy precipitation (pluvial or snow) can cause an overload on roof structures. Structures should be designed to resist precipitation loads, as well as impact from debris driven down a slope (LaRiMiT, 2016)

Typical details on traditional buildings to shed rainwater should be respected and **maintained**, such as **eoverhanging eaves, cornices, hood mouldings** and **sills**.

Various adaptations to a building's primary structure can be implemented to mitigate precipitation-induced landslides. Adequate **ground preparation** is necessary to ensure foundations will not settle/ displace in the event of high precipitation. Landslide mitigation measures include options such as (LaRiMiT, 2016):

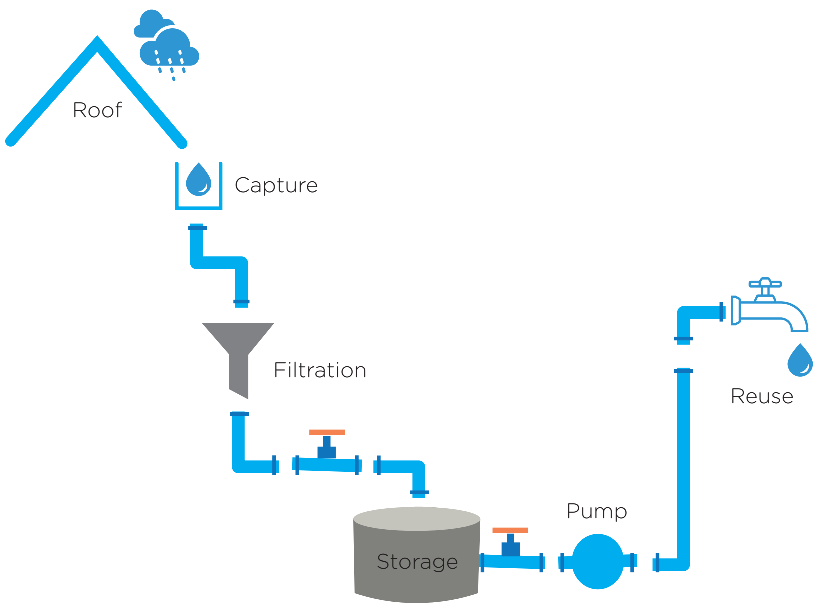
- erosion control measures (geotextiles, rip rap, turfing);
- modifying the slope geometry;
- surface and groundwater drainage works such as sub-horizontal drains and vertical wells;
- modifying the mechanical characteristics of unstable mass (compaction, jetting, cementitious grouting);
- mechanical transfer of loads to more competent strata (soil nailing, caissons, strand anchors);
- retaining structures to improve slope stability (stem walls, gabions, crib walls);
- passive controls for deviating landslide (baffles, deflection structures, barriers).

3.2.10. Services

Drainage networks should be **dimensioned** to future predicted climate-change induced water runoffs. **Attenuation methods** such as oversized gutters and downspouts, SuDS, blue roofs and attenuation tanks can reduce the impact on existing drainage networks.

Inside buildings, several measures can be taken to prevent inflow from sewage. These include **sewage pumps; anti return valves** for ground floor toilets and sinks; and, particularly for the design or renovation phase, the **placement** of **sinks** at a **minimum height** (for the Netherlands 150 mm, (STOWA, 2017)) above street level. Small temporary measures that can be taken are inflatable toilet closures and shower drain caps (Amsterdam Rainproof, 2022).

Figure 31: Rainwater is diverted from the gutters via a filtration unit for storage in large tanks and non-portable re-use (adapted from Kirton, n.d.)



Downspouts can also be connected to water storage solutions such as rainwater tanks to provide grey water for toilets or watering plants during dry periods (Figure 31). Water collected in this manner is not suitable for drinking unless it is further filtered and exposed to ultraviolet treatment (Kirton, n.d.).

3.3 Technical assessments, guidance & tools

Future Cities Europe provides an Adaptation Compass, a guidance tool for developing climate-proof cities. This tool assesses climate risk for each region and provides potential adaptation measures. Many of the solutions mentioned are measures against heavy precipitation.

Local governments in Germany are responsible for providing risk maps for pluvial flooding (induced by heavy rainfall). An example of such a risk map for Wuppertal is available here: Klimawandel und Starkregen | Wuppertal

ClimateAdapt Netherlands made a Climate-Proof City Toolbox providing information on risks, measures and associated costs for flooding, drought and heat.

The French Government provides information on the risk and consequences of flooding, including the risk of flooding for each postal code at the Georisques website.

The Association of Cantonal Fire Insurance VKF's hail register lists building components that have been tested for hail safety in Switzerland.

The Institute of Historic Building Conservation (IHBC) has provided a review of techniques available for assessing moisture in traditional porous building materials.

The Multifunctional Roofs Tool assists in investment decisions for multifunctional roofs including blue-green roofs.

Historic England provides a useful guide to restore traditional windows: Traditional windows their care, repair and upgrading.

3.4 Case studies

FloodCitiSense is a Joint Programming Initiative Urban Europe project with the aim to develop a **crowdsourced early warning system** for floods caused by heavy precipitation. Data on rainfall is collected by low-cost sensors and long-range technology and information is gathered by citizens. The information on rainfall helps city administrations to adjust official warning systems. The application is tested in Birmingham (UK), Brussels (BE) and Rotterdam (NL).

Rain gardens, swales and basins are put in practice in Groundwork London and Hammersmith & Fulham Council: **Climate-Proofing Social Housing Landscapes – Groundwork London and Hammersmith & Fulham Council** — Climate-ADAPT (europa.eu).

A sustainable urban drainage system was developed in **Augustenborg, Malmö** (SE), based on r**etrofitting the existing** one with a 6 km length of canals and water channels and 10 retention ponds. Supplementing the SuDS, more than 11 000 m2 of rooftops on existing buildings were retrofitted to green roofs. The total annual runoff volume is reduced by about 20 %..

Basel (CH) had the largest area of green roofs per capita in 2019. An amendment in the City of Basel's Building and Construction Law states that **all new** and **renovated** flat roofs must be greened and specifies design guidelines, such as minimum thickness and use of native plants. The Energy Savings Fund funded incentive programmes for these green roofs, providing subsidies for green roof installations for new buildings and for retrofitting existing buildings. The case of Basel shows that climate mitigation and adaptation can be compatible.

Hamburg (DE) developed a **Green Roof Strategy** with a goal to plant a total of 100 hectares of green roof surface in the city in the next decade. Part of the strategy is made up of financial incentives, dialogue, regulation and science. The Hamburg Ministry for Environment and Energy provides subsidies for building owners, up to 60 % of the installation costs. HafenCity University performs research on the question as to whether green roofs provide an adequate retention service.

Building owners in **Sweden** can receive a **climate screening,** to identify any climate risk their property might face. Risks associated with multiple hazards, including **downpours** and **flooding** are assessed, and advice on preventative action is given. This is provided by a real estate trade association.

3.5 Industry actors

3.5.1. Government, Regulators & local authorities

The risks of heavy precipitation and pluvial floods vary per region. Cities and regional governments should **measure** and **monitor** the **effects of flooding** on their area so that they can formulate adequate coping strategies. Amsterdam, Copenhagen, Oslo, Lisbon and other non-European cities are part of the Urban Flooding Network, as part of the C40 Cities Network, to support measuring and monitoring, exchange tools and strategies. See Urban Flooding Network - C40 Cities for more infomation.

Local government and municipalities play a role in supporting water storage in and around buildings in regions with an increased risk of heavy precipitation. They can do this, for example, by adding a condition on the **installation** of a **water retention system** in the **permitting process** for new buildings. This can be enhanced with requirements to design water retention and drainage systems for longer flood return periods (e.g. 100+ years).

Another way to stimulate climate adaptation in buildings against heavy precipitation is to provide **funding** or **subsidies** for **specific climate adaptation measures**. For example, Hamburg installed a fund to finance green roofs, as a partial solution for water retention.In doing so, it is important to investigate the effectiveness of the stimulated measure for the purpose of climate adaptation in the region. For example, where most roofs are inclined rather than flat, green roofs will be less effective for water retention, but stimulating green gardens might be appropriate.

3.5.2. Investors, developers & insurance providers

Insurers and investors should consider the risks of heavy precipitation specific to a region. This can be done by assessing previous damage claims and the type, amount and duration of heavy precipitation associated with them. Climate projections sug-gest an increase in heavy precipitation events, however the distribution of these is uncer-tain. It is important to incorporate this uncertainty given the long lifecycle of new buildings.

European insurers are expected to **integrate climate-related risks**, including extreme rainfall and hailstorms, into their **own risk and solvency assessments (ORSA)**, as expressed by the **European Insurance and Occupational Pensions Authority (EIOPA)**. Insurance providers could set up an insurance scheme promoting implementation of property level flood protection measures to mitigate associated risks, specific to the regions. Developers should integrate these adaptation measures in their projects accordingly.

3.5.3. Design teams (engineering and architecture)

When developing designs for new buildings, it is important to **anticipate much higher levels of heavy precipitation**. Buildings tend to have a longer lifecycle than climate models can now accurately predict, and previous predictions have underestimated the speed at which the climate changes (Nationaal Kennis- en innovatieprogramma Water en Klimaat, 2022).

Regional effects due to climate change can affect the efficiency of the nature-based solutions described in Section 2.3.2 if not considered properly. Plants can face heavy precipitation and droughts over a short or long period of time in the same region. It is therefore important to **investigate the future regional climate projections** and **choose vegetation accordingly**.

When designing blue-green roof solutions, designers will have to consider a variety of factors:

- **Structural load:** the structural capacity of the proposed or existing roof must be considered when integrating blue-green roofs. The loading can vary significantly depending on whether the roof is intensive, extensive, has solar panels or is required to retain water.
- **Vegetation:** plants chosen as part of the design of a blue-green or green roof require several considerations. The plants should be adapted to the expected rainfall patterns of the region so that watering and droughts as a consequence are limited. The use of indigenous and non-invasive species is preferred so as to prevent disruption to the ecosystem. Moreover, a variety of plants should be used to have a benefit of increased biodiversity.
- **Drainage:** the design of the blue-green or green roof should ensure that obstructions in gutters, and freezing within gutters, can be easily prevented.

In the **choice of materials**, the resistance to hail should be considered in regions at risk. Examples are a hail protection grid made of polycarbonate for the roof; thermoplastic polyolefin waterproofing membrane for mechanically fastened roofs; or window shutters made with an extruded aluminium profile. An overview of hail-proof materials for roofs, windows, etc. can be found at the hagelregister website.

3.5.4. Building users, facility managers and owners

Building owners and users have a significant role to play into making buildings more resilient to heavy precipitation. The tools described in Section 3.3 may support building owners and facility managers in assessing a building and identifying improvements. In high-risk areas, there are additional measures buildings users can apply to prevent damage from heavy precipitation.

These measures support either:

- **an increasing water infiltration rate:** measures include removing tiles around the building and replacing them with plants; the installation of green facades or the installation of anti-return valves in sanitary pipes; or
- **a reduction in the risk of sewerage overflow:** measures include disconnecting rainwater drainage from the sewage network and instead connecting it to a rain barrel, water storage or a soak away into the ground.

4. Flooding

4. Flooding

4.1 Description

Flooding may occur as an overflow of water from rivers (fluvial flooding) or as an accumulation of rainwater on saturated ground (pluvial flooding). An increased severity and frequency of floods is anticipated in Europe due to climate change (WMO, 2021).

Rising sea-level can cause coastal flooding, especially when combined with temporary events such as high tides or storm surges. About 75 % of European countries with a coastline plan for a sea-level rise, but 25 % do not (McEvoy, 2020). To protect against the growing risk of flooding, it is important to understand the impact and to take appropriate adaptation measures to building and their surroundings.

Buildings can be vulnerable to flooding, especially when located at the bottom of a slope or on low terrain, and in areas with low infiltration rates. Flooding impacts basements, ground floors, street level access to buildings and, in some cases even the entire structure.

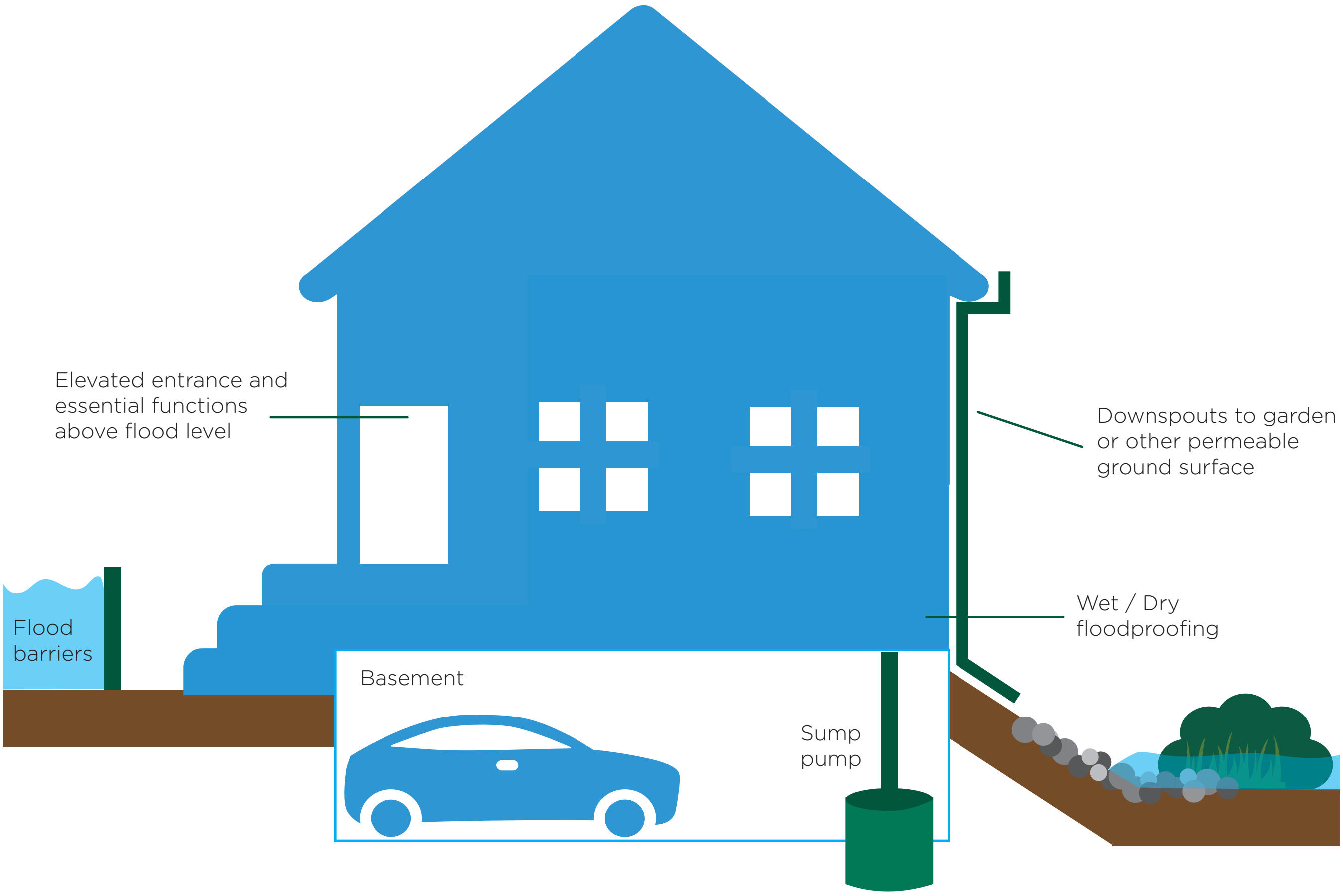
4.2 Description

Solution	Element	Impact on other hazards	Key considerations
Square shape	Building shape	! Storms ! Heavy precipitation	! Long walls should not face the direction of flow Not suitable for a retrofit or renovation
Buoyant foundation in amphibious buildings	Foundations	N/A	Not suitable for a retrofit or renovation
Elevated structure	Foundations	+ Subsidence	Not suitable for a retrofit or renovation
Primlinary soil study	Foundations	+ Heavy precipitation	N/A
Wet floodproofing (vents, internal drainage system, etc.)	Foundations	+ Storms + Heavy precipitation	+ Cheaper than dry proofing ! Extensive clean-up required after flood, risk to health.
Water resistant materials (plaster-based coating or water-repellent mortar)	Walls & Preferred materials	+ Storms + Heavy precipitation	! Possible decrease in breathability
Permanent flood barrier (automatic barriers, flood walls, retractable barriers)	Windows & doors	+ Drought + Storms + Flooding	N/A
Temporary flood barriers (flood shields, sand bags, deployable and inflatable barriers)	Windows & doors	+ Drought + Storms + Flooding	N/A
Water repellent finishes	Preferred materials	+ Heavy precipitation + Storms ! Heat waves	! Most materials cannot be used as insulation material ! Impermeable materials can prevent breathability and contribute to overheating in high temperatures.
Water-resistant insulation (expanded polystyrene – EPS – and extruded polystyrene – XPS)	Preferred materials	+ Storms + Heavy precipitation + Hea twaves	+ Reduction in energy demand
Water-resistant materials	Preferred materials	+ Heavy precipitation + Storms	! Risk of carbon emissions from intensive materials

Priority hazard: Flooding

Solution	Element	Impact on other hazards	Key considerations
Electrical and mechanical systems and utilities above flood level	Services	+ Heavy precipitation + Storms	N/A
Buffer zones around the building	Space considerations	+ Heavy precipitation	N/A
Drainage system around the building	Space considerations	+ Storms + Heavy precipitation	N/A
Tree planting	Vegetation	+ Heavy precipitation + Storms	N/A

Figure 32: Overview of adaptation solutions for flooding



These solutions will be appropriate for different levels and duration of flooding. For short-term floods, and with a low flood level (up to 0.3 metres), an early warning system in combination with temporary shields of openings to buildings and moving essential functions up in the building might be sufficient. In regions that are prone to floods of long duration, or high flood levels, more drastic solutions will be required, such as adequate foundations and the use of water-resistant materials.

Most of the solutions mentioned in the section of heavy precipitation contribute to mitigating the effect of pluvial flooding. The vegetation and nature-based solutions described in Section 3.2.6 mitigate the effects of all types of flooding by increasing the infiltration rate of the ground around a building. This should be considered in combination with solutions to flooding, in order to minimise the total flood damage.

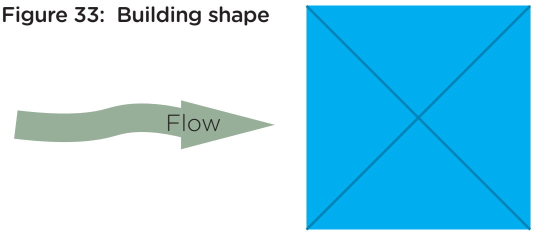
4.2.1. Building shape

The shape or floor plan of the building and its orientation to the direction of water flow are factors that affect the structural resistance of a building in the event of a flood. Specialist structural engineering advice should be sought for any building designed specifically for flood risk. However, in general **square building shapes** are favourable as they are more resistant to horizontal loading from flood wate.r

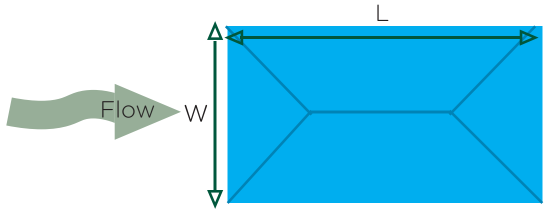
Long and narrow building shapes intercepting the direction of flow should be avoided (see Figure 32). i.e. the orientation of the building should be such that the longer walls should not face the direction of flow.

Narrow spaces between buildings can cause high velocity water flow (and debris) that might impact walls parallel to the flow (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006).

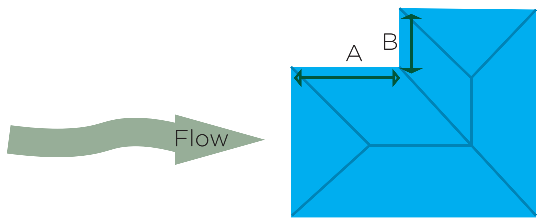
Figure 33: Building shape



Square shaped houses are preferred as they are generally stronger in flood conditions



If rectangular houses cannot be oriented along the flow as shown, keep L less then double side W



If the longer leg of L-shaped houses cannot be oriented along the flow as shown, keep side A less than 1.5 times side B

4.2.2. Foundations

The first consideration should be to build the structure above flood levels to minimise damage when flooding occurs. This can be done by **elevating a building** on columns or stilts, or simply raising the solid foundation (Cao, 2021). However, foundation design should take into account uplift and potential damage from strong winds.

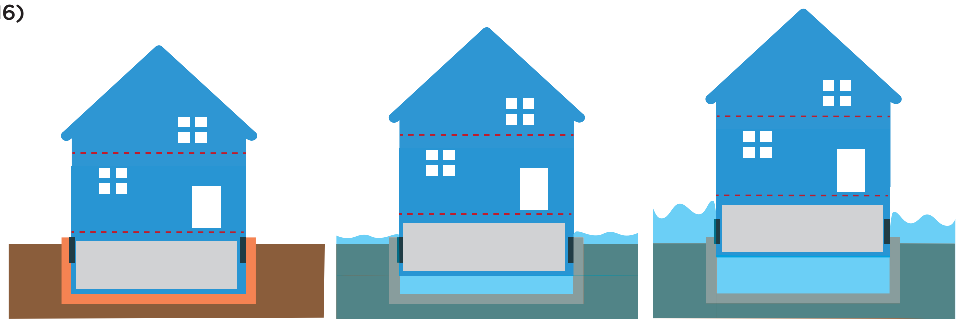
Soil permeability affects water infiltration on the site, which in turn influences the safety of the foundations or basement structure. Therefore, a **preliminary soil study** in order to detect all risks of ground movement should be done.

Measures to **control** the **humidity level of the soil** and preserve the integrity of the building foundations may be required (Observatoire de l'immobilier durable, 2021). The use of fill material in foundations should be avoided in flood-prone areas, as this can make foundations vulnerable to erosion and local scour. In areas prone to coastal flooding, the design of foundations should consider all forces resulting from flooding, including wave action, debris impact, erosion, and local scour (FEMA, 2011). When soils are susceptible to erosion and local scour, structures should be supported on **deep footings** or **foundations**.

Shallow foundations should be designed to **prevent sliding, uplift,** or **overturning** due to flood loads. Existing low-rise buildings are commonly built on shallow foundations. Flooding is unlikely to lead to serious structural instability unless there is a significant wash-away of the supporting ground. This can be avoided by ground strengthening measures.

Building on floodplains requires specialist input; buildings can be designed to float either as a floating building or as an amphibious building. **Floating buildings** can rise and fall in response to rising water levels whereas **amphibious buildings** are built on the ground but have the ability to float if water floods the area (see Figure 33) (A Better City, 2015). An amphibious building has a buoyant foundation so that it can float whilst vertical posts restrict horizontal movement and subframes support and stabilise the building (English et al., 2019).

Figure 34: The amphibious house floats when the area is flooded while being constrained by poles (adapted from Baca Architects, 2016)



Priority hazard: Flooding

Two strategies for floodproofing can be considered when designing the primary structure (A Better City, 2015):

- **Dry floodproofing** prevents water from entering a building in a flooding event.
- **Wet floodproofing** approaches allow for temporary flooding of the lower parts of the building through the use of openings or breakaway walls.

Wet floodproofing methods can include **stilts** or a **sacrificial basement** (uninhabitable spaces such as car parks). (see Figure 35). Allowing basements to flood ensures hydrostatic forces will balance out and reduce stress on the retaining structure. The lowest floor should be designed to account for flood loads acting simultaneously with wind loads, and should be adequately anchored by using piles to prevent flotation. Load from debris impact or the creation of barrages should also be considered during the design. The sub-structure should be waterproofed with saltwater-damage-resistant materials to ensure it is resistant to flood conditions.

Breakaway walls are intended to limit flooding damage by collapsing under specific lateral loads and relieving water pressure without damaging the primary structure. This approach is suited to cavity-walled masonry buildings, in floods greater than 0.60 metres deep as the structural integrity of such buildings can be jeopardised (Lymath, 2014).More information on breakaway walls can be found in FEMA's Design and Construction Guidance for Breakaway Walls (2008).

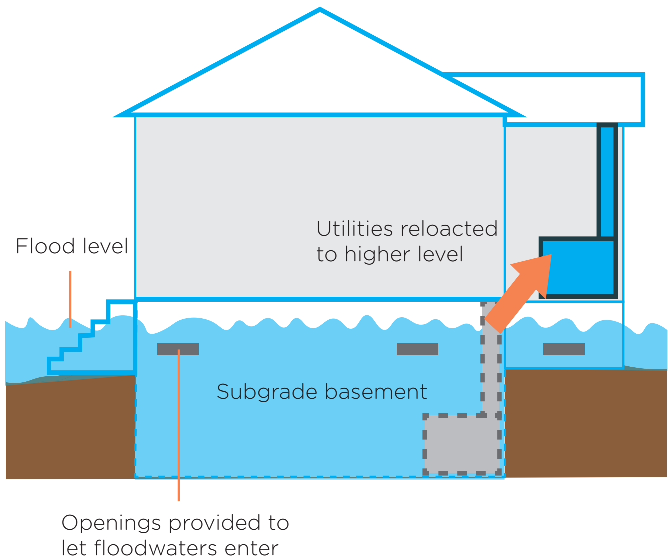
Another example of wet floodproofing is the installation of **foundation vents** or an internal drainage system such as **sump pumps**. The vents allow some water to flow in the building rather than pool around it, thus reducing the pressure of floodwater on windows and walls. If the interior is prepared using flood-damage-resistant materials, hydrostatic openings and protected key equipment, the damage can be limited (Cao L., 2021). Similarly, a sump pump is a type of equipment that pumps water out of basements. When flooded, sump pumps are powered by electricity; backup generation or a battery-operated backup may be necessary in the event of power outages during extreme storms (A Better City, 2015).

Dry floodproofing aims to make a building watertight below the flood level. Dry flood proofing can be done in existing buildings as part of a retrofit; however careful consideration is required as to the materials used and their potential impact on the breathability of the building fabric (see Section 4.2.7 Preferred materials, for further details).

Impermeable membranes and **sealants** can be applied to the exterior wall face. This seals a wall, reducing or preventing the penetration of flood water through the wall. During the construction of new buildings, a water-resistant layer of asphalt or plastic can be applied.

Temporary flood shields can be installed in preparation for potential flooding, or after a flood warning is issued. Flood shields are typically made of aluminium, stainless steel, or plastic and use neoprene rubber or similar materials to seal the barrier.

Figure 35: Allowing the building to flood with a wet floodproofing strategy reduces hydrostatic pressure, reducing loads on walls and floors and decreasing the risk of damage to the structure (A Better City, 2015). Diagram adapted from: A Better City, 2015 and FEMA, 2014b



Inside the building, **devices** to **prevent backflow** can be installed on sewage pipes to prevent contaminated water from flowing back into a building through the plumbing due to flood-induced sewage overflow (A Better City, 2015).

Sump pumps can also be installed to compensate for leakages inside basements. If dry floodproofing techniques fail and water is able to enter the building, installing impermeable flooring in the basement will help to minimise damage (and associated repair costs) (Sustainable Buildings Initiative, n.d.). Polished ground slabs are impermeable and if installed properly, will not need replacement after flooding (A Better City, 2015). For buildings located in areas vulnerable to flooding, dry floodproofing will be most effective when multiple measures are combined.

Overall, wet floodproofing has several advantages over dry floodproofing. Firstly, wet floodproofing approaches are often less expensive, in both new construction and retrofits. Secondly, wet floodproofing prevents severe structural damage which can occur when design loads are exceeded in flood conditions. However, wet floodproofed buildings may require an extensive clean-up after a flooding event. Buildings may be exposed to contamination and health risks if floodwaters carry sewage, chemicals, or other pollutants into the building (A Better City, 2015).

4.2.3. Walls

The walls of the building that are at greatest risk from flooding are in the lower part of the building, and therefore part of the foundation and basement. To preserve the interior spaces and particularly the lower floors, it is recommended to select **water-resistant materials**.

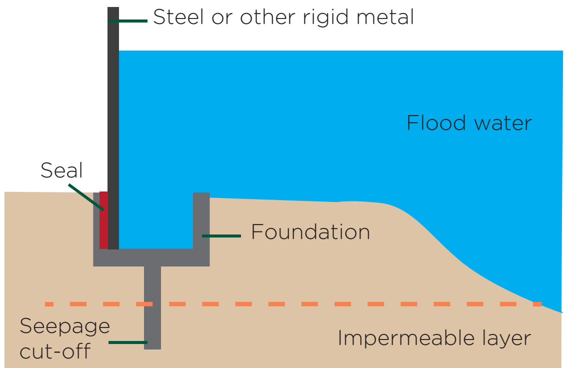
For the outer envelope of the building, it is recommended to waterproof the walls (from the inside for the above-ground parts and from the outside for the buried parts) using, for example, a plaster-based coating or water-repellent mortar (Observatoire de l'immobilier durable, 2021),

4.2.4. Windows and doors

Temporary barriers to windows and doors are often an effective and low-budget measure to protect against floods. Examples of barriers are **flood shields** for windows and doors (see Figure 35), **sandbags** for main entrances, and **deployable and inflatable barriers.** These are relatively inexpensive, can be placed in various positions, and removed when waters retreat (BBC, 2022).

Flood barriers can also be installed in a **permanent** manner. These can be appropriate for windows and doors that are below a floodplain and are therefore the first to flood in the case of high water. These can include **automatic flood defence** barriers that rise up when needed, flood walls, and retractable flood barriers. Regular maintenance will be necessary to ensure the barrier is ready for deployment when a flood occurs (Low et al., 2013).

Figure 36: Temporary lightweight metal sectional flood barrier.



4.2.5. Roof

Several roof-adaptations to protect against pluvial flooding are described in Section 2.2.5 as part of solutions for heavy precipitation. Fluvial flooding and flooding due to sea-level rise are not likely to affect the roof of a building.

4.2.6. Vegetation

Vegetation increases the infiltration rate for water around the building. The roots of **trees** increase ground stability and can provide protection against landslides as a consequence of flooding. **Wetland vegetation** such as reeds and willows help to work towards this purpose by catching sediment with their roots, lowering wave heights, and reducing flow velocity through friction (WMO, 2012). Several vegetation and nature-based solutions to retain water are described in the solutions for heavy precipitation and are also relevant flooding solutions.

4.2.7. Preferred materials

Flood resistant materials are materials that can withstand water for at least 72 hours, without significant damage. Examples include:

- stone or concrete, for floors;
- polyvinyl chloride (PVC), aluminium or steel, for interior joinery;
- cold formed steel partitions;
- polythene floor membranes or water-resistant floor finishes;
- glass, metal, ceramic and some types of plastic, for other interior finishes;
- water resistant insulation such as expanded polystyrene (EPS) and extruded polystyrene (XPS) rigid foam panels, can be used an alternative to mineral wool (Observatoire de l'immobilier durable, 2021).

If the building is designed to be resistant to short-duration flooding, for example if the basement is intended to be used for non-essential functions only (such as parking or storage), the outer walls and floors can be lined with water-resistant concrete to improve flood resilience.

Some common building materials do not provide flood protection and therefore may not be suitable in flood prone regions. Timber facades, composite masonry and ventilated double skin walls will allow water to flow into voids, leading to soaking. Timber is susceptible to decay following flooding, unless it is adequately protected and dried out in a timely manner.

For existing buildings, special coatings or base plaster for waterproofing masonry, stoneware tiles or metal profiles can be retrofitted to the building.

The flood-resistant material solutions presented in this section may not be appropriate for heritage buildings. Such materials applied to traditional construction may be damaging, affecting the necessary breathability of the building fabric, reducing its energy performance and potentially promoting mould growth (with consequences for the well-being of the building's occupants). Temporary flood barriers such as sandbags, flood shields or inflatable barriers can provide protection to entrances and openings, without altering the building fabric.

4.2.8. Space consideration

In order to combat hydrostatic and buoyancy force, appropriate buffer zones around a building should be installed with a setback distance from the edge of the flood hazard area. The fill soil should be homogeneous and of a low permeability. A drainage system installed around the building's foundations with a sump pump can reduce the amount of infiltration into the soil and make the structure safer (Low et al., 2013).

4.2.9. Primary structure

Historic buildings should be preserved during flooding events following the consultation of experts such as a Historic Preservation Officer and a design professional (engineer or architect).

Signs of structural damage include bulging or dislodged sections of masonry caused by heavy impacts, excessive pressure or undermined foundations, especially at corners. Significant cracks above doors and windows and at the ends of facades, and any major leaning, tilting and subsidence of the structure that was not evident, or was not as pronounced, before the flood would need specialist investigation (Pickles, 2015).

4.2.10. Services

Electrical and mechanical systems and utilities may be placed overhead. When designed for submerged installations, the buried portions of underground electrical utilities are also generally resistant to flood damage, but above-ground components of underground electrical utilities such as below-grade electrical vaults, pad-mounted transformers, pad-mounted switchgear, and electrical substations can be damaged by floods when located below the flood level (Low et al., 2013). Electric circuits below the flood level should be on a separate circuit from the one above flood-level.

4.3 Technical assessment, guidance & tools

Klimaateffectatlas shows the risk and impact of flooding up to the year 2050 for the Netherlands.

The Bat-ADAPT climate change risk exposure map shows the risk of flooding across France.

The Federal Emergency Management Agency (FEMA) has prepared the Homeowner's Guide to Retrofitting: Six Ways to Protect Your Home From Flooding providing homeowners with straightforward guidance.

Flood resilience in Italy: Acting Together describes a probabilistic, high resolution flood model that can be used to assess accumulation risk and single risks in Italy.

Floodprobe, is a European research project that, provides guidance on cost-effective solutions for reducing flood risk in urban areas, including a list of materials for wet proofing and dry proofing.

Adaptation Scotland provide a guide on Climate Change Adaptation for Traditional Buildings, with a section focused on flooding.

Hochwasser - BBK (bund.de) provides practical information for residents in areas with a high risk of flooding.

Mosaicature Nazionali ISPRA pericolosità frane alluvioni provides information on flood hazard zonation in Italy.

Some of the solutions, such as flood barriers for entrances, need to be taken right before the start of a flood. The European Flood Awareness System, provides flood and flash flood notification services for Europe.

To ensure the use of sustainable water-resistant materials, consult the UK's Technical Guide Code for Sustainable Homes drafted by the BREEAM Centre.

4.4 Case studies

In **Boscastle** (UK) measures were taken after floods in 2004: **impermeable wall finishes were replaced by limewash** to allow walls to dry out after flooding; electrical points were raised off the ground; floors in the youth hostel were raised above the flood level of a 1 in 100-year flood.

In the **Eferdinger Beckenm** (AU), **relocation** was used as a way to adapt to flooding. The federal and regional government compensated citizens in an area with no protection against flooding if they agreed to move. For more information see Relocation as adaptation to flooding in the Eferdinger Becken, Austria — Climate-ADAPT (europa.eu)

In **Hillerod** (DK) external ponds and streams were made for **water storage** around a hospital, in order to ensure access to the hospital in times of heavy rainfall. For more information see New North Zealand Hospital: A resilient acute care hospital for the future, Hillerød, Denmark — Climate-ADAPT (europa.eu)

Rotterdam (NL) built its **first floating street** with floating houses that move with tides of 1.5 to 2 metres. The houses clean their own wastewater and produce their own electricity.

The cities of **Trondheim** (NO) and **Amsterdam** (NL) have built **houses on stilts** in the past. The same technique can be applied for new buildings, though water resistant materials should be considered.

4.5 Industry actors

4.5.1. Government, regulators & local authorities

Within Europe, several countries have issued tools with **online maps** to **assess the risk of flooding for locations**, with information on the expected height and duration of floods. Making this available is key in planning flood-adapted buildings. This information should also incorporate up to date data on changing sea-levels and precipitation patterns to ensure a comprehensive overview of flooding risks.

Local, national and European governments should provide an early warning information distribution service to their citizens in case of a flooding event. This should give citizens time to prepare in case of high-flood risks, through push messaging or broadcasting via news stations. **Early warning systems** are considered one of the most cost-effective measures to prevent damage by flooding, according to the Global Commission on Adaptation.

The EU Floods Directive requires EU Member States to assess the risk of flooding and set up flood management plans following an international framework. Governments are required to form a coping management strategy for areas with a high risk of flooding. This can include the stimulation of a range of solutions up to, where necessary, planned relocation. Coordinated flood management planning is particularly relevant for transnational regions prone to flooding.

Government led-planning and policy development is important in stimulating building adaptation solutions for the regional environment. **Planning based solutions** include limiting building on flood plains through permitting and land use regulation.

Public-policy driven adaptation can include early warning systems, establishing flood response committees, government-led flood awareness campaigns and national disaster response mobilisation (UN 2021).

4.5.2. Investors, developers & insurance providers

Insurers can make use of flood maps to identify high flood risk regions. Insurance companies play an important role in **risk awareness** and **communication** (Comité Européen des assurances, 2005). Some European countries have their own **flood risk zoning** and **mapping tools**; for example, HORA in Austria; FRAT in Czech Republic, ZÜRS Zonierungssystem für Überschwemmung, Hochwasser und Rückstau in Germany.

Insurers play a role in promoting flood prevention measures through publicity and guidance at the property level. Please see the following link for a case study for insurers: Insurance company supporting adaptation action in small and medium sized enterprises in Turin (Italy) — Climate-ADAPT (europa.eu).

4.5.3. Design teams (engineering and architecture)

Design teams need to consider future projected flood levels and flood types anticipated for their local region. The BREAAM International New Construction Technical Manual provides information on how to **assess risks** and how to **comply with climate adaptation** in buildings, including flood risk. Solutions to mitigate risks for flooding, mainly on the primary structure, should be built in the design of buildings in flood-prone regions.

4.5.4. Building users, facility managers and owners

Owners of buildings need to ensure that the people inside the building are **prepared** and **equipped to respond** to a flood event. The Austrian Government provides a checklist for building users on **risk** and on **actions**. Some of the actions are providing early information; ensuring important belongings are located on a floor above flood level; and installing temporary flood barriers. Comprehensive guides for building owners have been prepared by the Centre Européen de Prévention du Risque d'Inondation (CEPRI) (Flooding Risk: Identifying and reducing building vulnerability) and FEMA (Homeowner's Guide to Retrofitting: Six ways to protect your home from flooding).

5. Subsidence

5. Subsidence

5.1 Description

Climate change may significantly impact ground conditions. Changing precipitation patterns and variations in temperature affects soil moisture levels and composition. The shrinkage and swelling of soil is an increasing risk across Europe, as soils with a high clay content are highly sensitive to volumetric change (Swiss Re, 2011)

Subsidence occurs due to a change in soil volume underneath a building, causing the ground to become unstable and sink downwards. Subsidence can have a damaging affect on ground bearing foundations. Changes to soil volumes can be caused by the following dynamics:

- **Precipitation-induced subsidence:** periods of excessive and prolonged rainfall cause excess ground water levels to rise. More water seeping into the soil causes soils to swell.
- **Drought-induced subsidence :** an excessive and prolonged dry period causes soil shrinkage as the soil retracts due to water evaporation.
- **Vegetation-induced subsidence:** subsidence can also result, or be further magnified, by tree-induced ground movements. Tree roots (particularly willow, elm, ash and oak) extract and absorb water and moisture from the soil. A drought will cause subsidence if trees absorb more water than is available. Hence, the proximity of tree roots to the building's foundations can increase the risk of subsidence during a period of drought.

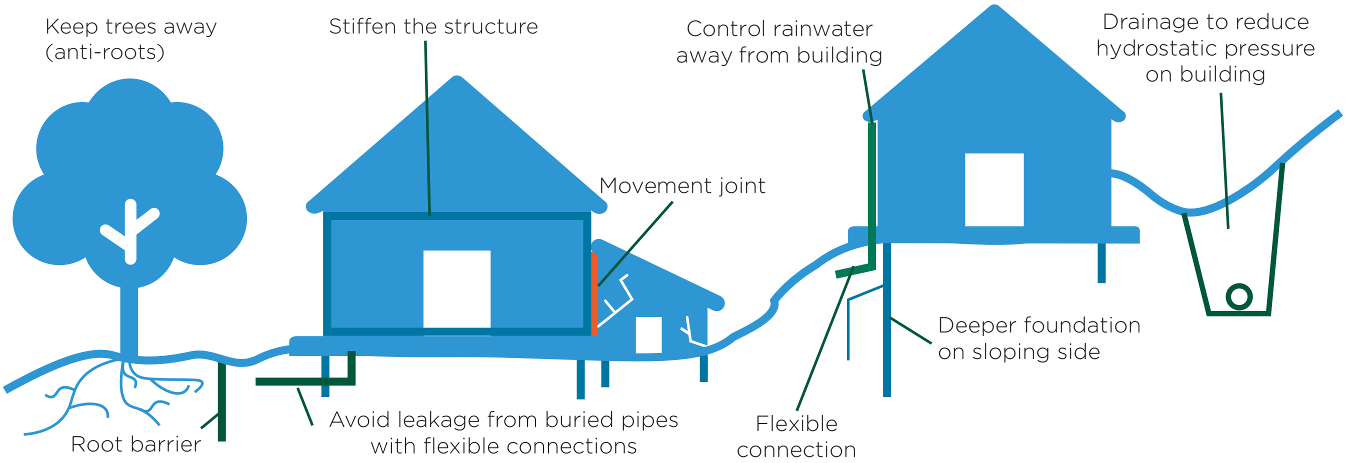
It is important to note that human activities can also cause subsidence; for example, the exploitation of groundwater, old in-filled sites such as excavation workings and land reclamation areas are all vulnerable to subsidence. Climatic variations may also exacerbate soil vulnerability to subsidence from pre-existing effects from human actions. The guidance and solutions presented in this report specifically address how buildings can adapt to subsidence related to climatic variations. Other solutions may be more appropriate for subsidence caused by human interventions.

Soil movements occur typically within a 5-metre depth from the ground surface and rarely more than 150 mm horizontally or vertically. Pronounced soil movements are a major risk due to the potential material damage they cause to the structure of buildings, hence posing serious risks to the user's safety. The following section presents technical solutions for how a building can adapt to subsidence.

5.2 Solutions

Solution	Element	Impact on other hazards	Key considerations
Greenspace management regimes	Vegetation	+ Heatwaves + Storms + Drought	! Consideration to the species of plants as this affects the recommended distance away from the foundations
Impermeable peripheral pavement around the building	Space considerations	+ Storms	N/A
Peripheral drainage system	Space considerations	N/A	N/A
Keep trees at a safe distance from the building and keep the amount to a minimum	Vegetation	! Heatwaves ! Heavy precipitation ! Flooding + Storms + Drought	! Consideration to the species of trees as this affects the recommended distance away from the foundations
Deep or semi-deep foundations	Foundations	+ Storms + Drought	Not suitable for a retrofit or renovation
Underpinning	Foundations	N/A	! Suited to buildings that have already suffered from the effects of subsidence to prevent further damage
Homogenous foundations (avoid partial basements)	Foundations	N/A	Not suitable for a retrofit or renovation
Structural strengthening (horizontal and vertical reinforcements)	Wall	N/A	! Requires significant structural work and is therefore best suited for new buildings or existing buildings under renovationn
Movement joints	Wall	N/A	N/A

Figure 37: Overview of adaptation solutions for subsidence



5.2.1. Building shape

[Not applicable]

5.2.2. Foundations

Shallow foundations are more vulnerable to subsidence. These are typical in low-rise buildings and historic buildings. Foundations need to be deeper in the zones most affected by variations in moisture levels so **deep, or semi-deep foundations**, are recommended. The deeper the foundations, the more they will limit the effects of shrinkage or swelling on a structure as foundations reach the more stable ground. The recommended depth depends on the susceptibility of the soil to subside.

Foundations should be dug homogeneously around the entire perimeter of the building to avoid differential movement; this is particularly important for buildings located on sloping terrain. It is advised that partial basements resulting in differences in the founding level are avoided at all costs, particularly on a sloping terrain.

Appropriate structural foundation options should be considered. **Raft or piled foundations** may be suitable options, or **jet grouting** depending on circumstances and financial viability. If subsidence is encountered in an existing structure, **underpinning strategies** should be implemented.

After a subsidence event, underpinning foundations will prevent further damage. This includes raising, relevelling, and re-supporting a building with an additional foundation layer. Mass concrete underpinning, beam and base underpinning and micro piles are the most common traditional underpinning methods (Lymath, 2014). However, as the **appropriateness of the underpinning measure depends on the preconditions of the ground, surroundings, and building type**, engineers should advise on the most suitable strategy.

Traditional buildings (including historic and heritage sites) may have been built on rafts or shallow foundations. This makes traditional buildings particularly vulnerable to subsidence because the foundations can crack or settle when the ground subsides, as opposed to deeper foundations that can transfer the load further down the soil where there is less fluctuation. This vulnerability is further exacerbated when there has been an addition of modern services or alterations to the building. In these cases, a **ground engineering specialist** should be sought, with the aim of strengthening the ground and preserving the structure while reducing additional movement.

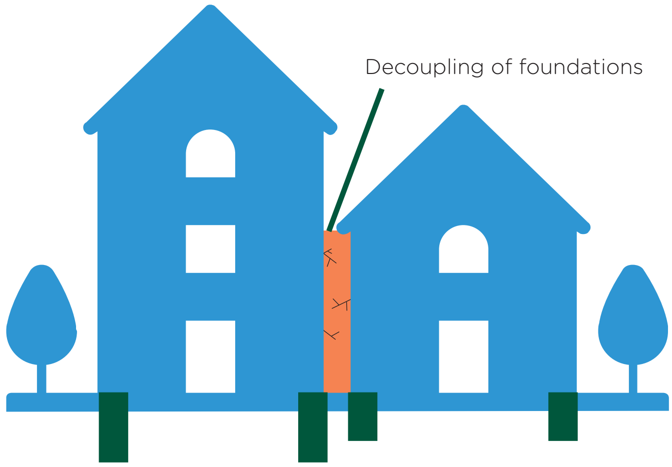
5.2.3. Walls

Buildings may not have the sufficient rigidity to resist and adapt to vertical and horizontal soil movements. Implementing solutions to strengthen the structure can provide additional stability. This should be done throughout the building structure.

Structural strengthening approaches include:

- tie rods;
- resin bonding;
- masonry stitching;
- corseting with reinforced concrete or post-tensioned ground beams;
- horizontal joint reinforcements placed in the horizontal mortar joints of the masonry-wall;
- vertical joint reinforcements for load-bearing-walls.

Figure 38: Decoupling of adjoining buildings with different foundation depths



The points at which the horizontal and vertical reinforcements meet at the corners of buildings require particular attention in all cases.

Structural strengthening requires significant structural work; hence this is best suited for new builds or existing buildings under renovation

In cases where adjoining buildings have different foundation depths, rigid wall structures can make the junction between the two structures vulnerable to cracking or detachment as the structures move at different rates. It is essential to incorporate **movement joints** are essential to incorporate in all building parts that do not have the same foundations, have different weights load or are built on ground conditions at risk of subsidence (Figure 38). The installation of movement joints allows the building frame / wall to adapt to soil movements by allowing each part of the building to move and adjust, thus helping to avoid damage from the different movement rates. Movement joints are well suited for projects that involve the extension of existing buildings.

Temperature variations can also lead to movement within the different walls of a building structure. **Expansion joints** provide a solution to adapt to temperature variations that can cause structural changes. These joints are more resilient to movement due to having expansion and deflection capabilities. Joints are most effective when implemented across the entire height of the buildings (including the foundations) (Ibstock Brick, 2021).

5.2.4. Windows

[Not applicable]

5.2.5. Roof

Diagonal strengthening across the length and width of the roof provides further stability.

5.2.6. Vegetation

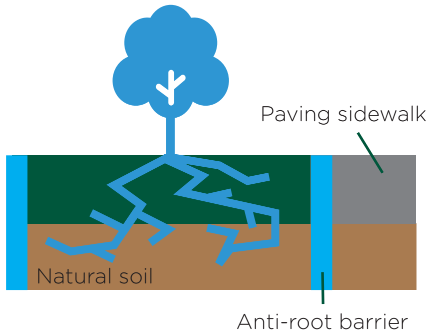
Subsidence can also result, or be further magnified, by tree-induced ground movements. Tree roots (particularly willow, elm, ash and qak) extract and absorb water and moisture from the soil which will cause subsidence if trees absorb more water than is available. Extensive vegetation, gardens, and gravel pavements next to buildings can cause water retention in the soil and changes in the moisture levels. This contributes to increasing the vulnerability of buildings to subsidence, particularly on subsidence-prone soils such as clays. Managing these eco-systems includes careful **consideration of size, species, and placement of trees.**

Vegetation management can avoid further subsidence in buildings, for which there are a series of vegetation management approaches:

- Although vegetation helps to reduce runoff and landslide risks at larger scales, trees can cause direct damage to a building when they abstract water from the soil leading to soil desiccation, shrinkage, and subsidence. **Trees** should either be removed or typically **nnot be placed within 1.5 to 2 times the height of the tree from the building**; those that are within this distance should be reviewed by an engineer. The recommended distance may depend on the species of tree (see British guidance in the tools section). This will have the most significant, and immediate effect, on the level of soil desiccation.
- If the removal of hazardous **trees** is not possible, the size of their **roots can be reduced by cutting them**, or digging a trench between the property and the tree. The trench must not be too close to the tree or the building so as to preserve the tree's stability.

This creates a permanent barrier against the roots (Figure 39). The depth of these must intersect the roots of the tree (2-4 metres, depending on the context).

Figure 39: Installation of root barriers



5.2.7. Preferred materials

As the frequency of droughts and subsidence events multiply over summers, the risk of cracking pipes will continue to increase. Pipe materials should be adapted to deal with these temperature extremes. Similarly, during winter, waterlogged soil may freeze, causing soil movements. Using **materials that offer pipes ample flexibility**, like polyvinyl chloride (PVC), is recommended as the materials minimise the risk of buried pipes cracking.

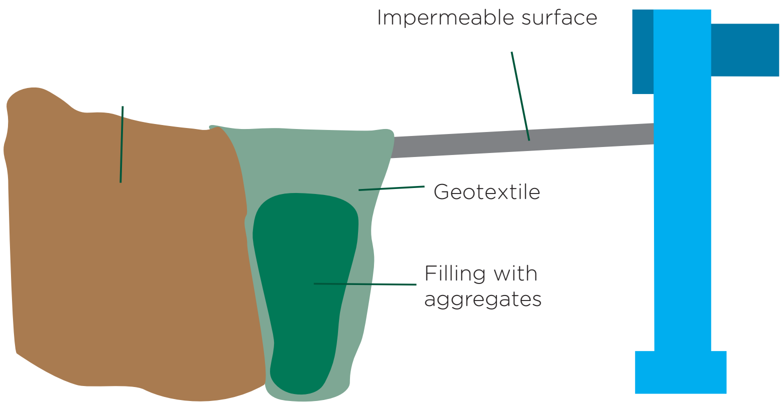
5.2.8. Space consideration

Soil located directly under the building is less exposed to evaporation than the surrounding soil that is subject to seasonal evaporation. The difference between the soils' water content can affect a building's foundations. The following approaches can reduce the risk presented by water level variations of the soil to both new and existing buildings:

- Placing an **impermeable peripheral pavement** around the building to direct water away from the foundations. The peripheral pavement can protect the soil in the immediate buildings' surroundings by limiting the possibility of water variations and avoiding the shrinking / swelling of soils. Impermeable materials, such as a geomembrane or concrete, can be placed around the building perimeter under the topsoil. The pavement should be a minimum width of 1.5-2.5 m. The efficiency of this method depends on the tightness of the pavement; considerations must also be placed on the drainage of runoff water (e.g. giving the pavement a slight slope).

  A collection system can also be installed to collect the runoff water and prevent it from seeping into the soil close to the building.
- **Installing a peripheral drainage system** (see Figure 40) helps keep moisture away from the foundations. The drainage system should be typically at least 2m away from a building to avoid saturating the ground.

Figure 40: Installation of a peripheral drainage system



5.2.9. Primary structure

Signs of damage and solutions for the primary structure are similar to those covered in Section 4 (Flooding).

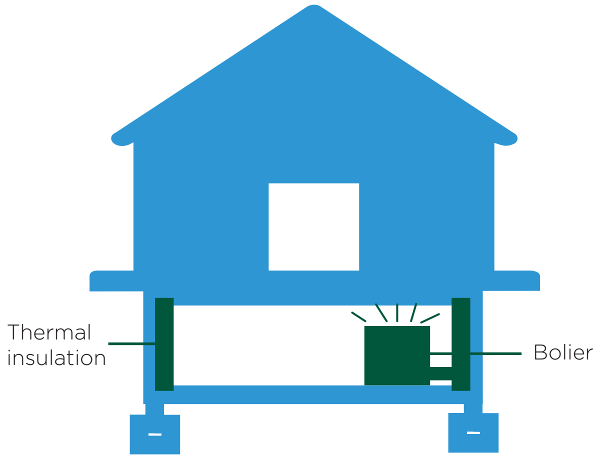
5.2.10. Services

Underground pipework, vulnerable to subsidence risk, can be protected by installing **flexible jointed pipework** (for drainage, gas, or water) and using flexible seals at the fittings.

Ensuring the proper **sealing of pipes** can prevent leaks associated with subsidence. **Regularly checking the tightness of buried pipe networks** located under or near the buildings is crucial particularly for existing structures with older rigid pipework, which can be more vulnerable to cracking.

In buildings with a heating system, or a heat source, such as a boiler installed in the basement of the building, the **heat exchange** through the walls must be **minimised** by installing **thermal insulation on the walls** (Figure 41). Thermal insulation is typically made from polystyrene or mineral wool.

Figure 41: Installation of thermal insulation to minimise heat exchange and cracking in foundation walls.



Another factor that causes, and further intensifies, subsidence is leaking drains and gutters. Leaking water can seep into the soil beneath the building's structure and wash away the soil foundations as well as cause water to saturate the ground. Foundations may then give way and subside. The installation of **systems to collect and dispose of roof water** is a relatively inexpensive solution that limits the water inputs at the foundation level. Roof water collection channels must be drained into a waterproof network away from the building foundations.

5.3 Technical assessment, guidance & tools

The Association of British Insurers (ABI) has provided home-owners with recommendations on safe distances (in metres) between popular tree species and homes.

Bat-ADAPT has developed a dynamic exposure map of France that presents the risk of exposure to subsidence hazards for specific building locations. Projections for 2030, 2050, 2070 and 2090 are available.

In France, the Evolution du logement, de l'aménagement et du numérique (ELAN) (translated as evolution of housing, development and digital technology) has made available a risk management system tool that enables buyers and tenants to assess the subsidence risk to properties.

EuroGeoSurveys' European Geological Data Infrastructure (EGDI) publishes Soil Regions Map, which can be used by many stakeholders to understand soil compositions and assist essential planning, design, construction, and maintenance decisions.

The French Government has produced guidance on preventative measures that can be taken to adapt new and existing buildings built on areas at risk of subsidence:

- Retrait- gonflement des argiles: Comment prévenir les désordres dans l'habitat individuel? (Ministère de la Transition écologique, n.d. (a))
- Construire en terrain argileux: la réglementation et les bonnes pratiques (Ministère de la Transition écologique, 2021)

There are standards available, such as ISO 16134 (ISO, 2020) for the design of earthquake-resistant and subsidence-resistant ductile iron pipelines; the application of these standards is suitable for areas affected by seismic activity and land subsidence.

NBS (National Building Specification) has gathered a comprehensive set of guidance on underpinning, subsidence and structural renovations (primarily from the UK). This includes publications from The Building Research Establishment (BRE), a building science research center.

5.4 Case studies

The **drought of 1976** in **France** led to multiple occurrences of subsidence that caused significant damage to buildings. In response, the government identified subsidence as a major risk and responded with **policy actions.** The mechanisms put in place provided a good foundation for the development of tools that have helped build resilience against current and future occurrences of subsidence. The publication of Article 68 of law no 1021-2018 of 23 November 2018 resulted in the development of a framework to **prevent the shrinking-swelling risk for buildings** along with the necessary construction and design techniques required.

This framework requires that the **ground conditions** and make-up of the soil, where the existing or future building is located, are **assessed**. In areas identified as medium or high exposure to shrinkage / swelling of soils, a soil study must be carried out (by either the seller when selling a building plot or the buyer must have a **geotechnical study** carried out for the builders and disclose information of the risk of ground movement so that best practice construction techniques can be applied). Additionally, the government has produced a risk prevention plan to regulate the use of land according to the natural risks to which it is exposed.

At the municipal level, the plan identifies areas exposed to shrinking / swelling of soils and make it a requirement to reduce the risk for new buildings, as well as existing buildings in the area. Depending on the hazard zone and their susceptibility to subsidence, the **recommended minimum foundation** depth varies. In low-to-medium hazard zones, authorities recommend a minimum foundation depth of 0.80 m. In high hazard zones authorities recommend a minimum foundation depth of 1.20 m, especially for individual homes, which are the most vulnerable to subsidence and the swelling of clays.

5.5 Industry actors

5.5.1. Government, regulators & local authorities

Public authorities can help industry actors take appropriate adaptation approaches, by investing in the development of methodologies and techniques to **monitor subsidence on a local/regional/national scale**. Improving the quality and quantity of publicly available data is critical to identifying areas that are **susceptible** or **exposed to shrinking / swelling of soils**. Governments should also seek to develop and encourage updated **risk assessments** across the construction industry. The case study in section 5.4 provides an example of government-led best practice.

5.5.2. Investors, developers & insurance providers

Investors and developers should consider their property or portfolio's exposure to soil subsidence, assessing both immediate and future risks. **Reviewing risk maps** and **soil composition maps** allows investors to understand the location of soils subject to clay shrinking / swelling and evaluate the composition of the foundational soils of buildings. **Geotechnical** and **soil surveys** can identify whether an early investment in subsidence adaptation or remedial interventions is needed.

Subsidence is not like other natural catastrophes from an insurance point of view, as it is difficult to determine causal links. In most countries insurance coverage for subsidence is still uncommon; buildings insurance will only cover the cost of repairing damage caused by subsidence but not for preventing further issues. As incidents of soil subsidence increase in frequency and severity with climate change, there is a need for **systematic risk adaptation through insurance** by developing guidance to inform other critical stakeholders on using insurance to support adaptation and disaster management, i.e., to identify what risk can be prevented and possibly insured. Insurers should understand the meteorological and geological indicators that make buildings vulnerable to subsidence and use the previously discussed soil assessment tools and indicators to identify risk levels.

5.5.3. Design teams (engineering and architecture)

Not all buildings are affected equally by subsidence. The vulnerability of buildings largely depends on the geological properties of the ground below, the properties of the surrounding area, and the building type. Design teams must perform a risk assessment and check the ground's structural stability by assessing the composition of soils and exposure to subsidence. Furthermore, design teams should use exposure maps and weather patterns predictions to evaluate how climate change impacts the soil.

Risk assessments should be part of the planning, design and the route construction checks carried out by experts. **Risk assessments** and **soil surveys** are critical to determining which subsidence adaptive building design is most appropriate. Inspections should be performed regularly after construction and throughout the lifecycle of the asset. Precautionary actions reduce the frequency of future costly interventions, such as underpinning.

5.5.4. Building users, facility managers and owners

Identifying subsidence is crucial for adaptation efforts. Early identification can inform remedial approaches and help prevent short- and long-term damage. The first sign is the appearance of cracks in a building's internal or external envelope, particularly following prolonged dry weather or drought. (AXA, 2022, E.surv Chartered Surveyors 2018) Other signs include:

- cracks wider than 3mm;
- vertical and diagonal cracking in isolated areas, usually wider at the top than the bottom;
- external cracking mirrored internally;
- opening and closing of cracks on a seasonal basis;
- cracking occurring around weak structural points, such as doors and windows.

If these signs are apparent, users should assess the structure and examine the ground to determine the vulnerability of the existing building. Additionally, users and buildings managers must **regularly check** and **maintain plumbing, drainage and stormwater systems**. Drains should be checked to prevent blockages and overflows. Below ground, facility managers can assess drainage network with rods and **cable- mounted CCTV probes** if defects are suspected. If a leak occurs, or minor damage and cracking in walls / ceilings appear, buildings users must cary out repairs immediately, to maintain good site drainage. The water content control systems described in Section 5.2.6 require monitoring and continuous upkeep to ensure that they prevent disturbances in the foundations and structure of the building.

6. Drought

6. Drought

6.1 Description

The European Drought Observatory defines a drought as the result from a shortfall in precipitation over an extended period of time (JRC European Commission, 2017).Rising temperatures, changing precipitation patterns and the overexploitation of water resources are expected to increase the frequency and magnitude of droughts throughout Europe (Kazmierczak et al., 2020).

There are three main types of droughts:

- **Meteorological drought:** amount of rainfall received in an area is less than the average, based on the degree of rainfall deficit and the duration of the dry period;
- **Hydrological drought; t**he impacts of a rainfall deficit on the water supply;
- **Agricultural drought:** the impact of a meteorological or hydrological drought on agriculture activities.

A drought can lead to soil moisture deficit, which limits water availability for natural vegetation and can accelerate soil degradation. Droughts and their associated effects post several challenges to a building's structure and to building users. Drought-induced subsidence, water supply shortages, extreme heat-induced damage to building materials and increased fire risk all threaten the safety and comfort of building users.

Drought adaptation measures for buildings focus on reducing water consumption, installing rainwater harvesting and recycling grey water.

6.2 Solutions

Solution	Element	Impact on other hazards	Key considerations
Air-handling unit (AHU) condensate capture and reuse	Services	+ Heatwaves	N/A
Designating water stressed areas	Space consideration	+ Heatwaves + Subsidence	N/A
Recycling grey water	Services	N/A	Recycled water should be re-used on site where possible.
Indoor water efficiency installation (Water-efficient fixtures and fittings)	Services	+ Heatwaves	! Requires regular checking and monitoring for leakages
Onsite water source such as onsite water storage or wells that can supply water for 4-3 days	Services	+ Heatwaves + Storms	Consider the storage location to ensure it is protected from sunlight
Rainwater harvesting	Roof	+ Heatwaves	Consider the storage location to ensure it is protected from sunlight
Nature-based solutions	Vegetation	+ Heatwaves	Select drought-tolerant species

6.2.1. Services

[Not applicable]

6.2.2. Foundations

Droughts and reduced groundwater levels can lead to soil shrinkage, vertical soil movements and drought-induced subsidence. This can cause damage to a building's foundations. For guidance on adapting to this hazard, refer to Section 5 on subsidence.

6.2.3. Wall

Drought-induced subsidence causes damage to the stability of buildings structure and walls. For guidance on how to address this issue refer to the subsection on walls in Section 5 on subsidence.

6.2.4. Windows

[Not applicable]

6.2.5. Roof

Long periods of drought result in water scarcity. Conservation and rainwater reuse are therefore vital actions, particularly in hot and arid climatic zones that are more susceptible to water shortages. **Rainwater harvesting systems** can help provide a continuous supply of water.

Rain barrels, or **cisterns,** installed on the building's roof, collect rainwater and divert rainfall water into storage tanks (see Figure 42). The system is a process of collecting, filtering, storing, and using rainwater to provide an alternative water supply. This can be used to irrigate gardens or other landscaping features, to maximize resource use.

If building users do not use the collected rainwater, it can be slowly released to recharge the groundwater. This approach will avoid runoff and reduce flood risk. When installing a rainwater harvesting system, the risk of summer droughts should be taken into account when deciding the tank's location, size and material composition.

Figure 42: Rainwater harvesting storage tanks placed below ground for heat protection

6.2.6. Vegetation

Nature-based solutions can protect, restore and create natural features that can reduce the impact of drought on a building. For example, **green roofs** and **green facades** reduce drought impacts by improving water retention and storage on roofs.

Conventional green roofs can be susceptible to droughts when additional irrigation is not available, so appropriate species must be planted, such as drought-tolerant sedums (succulent plants)and grass, (due their shallow-roots and low water use). **Green-blue roofs** are less susceptible to being compromised during a drought.

Refer to Section 1 on heatwaves for a detailed review of these approaches as they are primarily intended to adapt to overheating, but provide spill-over benefits when adapting to droughts. Vegetation-based solutions described in Section 5 on subsidence are also applicable for adapting to drought-induced subsidence.

6.2.7. Preferred materials

Extreme heat and lack of precipitation during a drought can shorten a building's lifespan and cause damage to materials. The moisture lost to drought can cause buildings materials to shrink and crack. For guidance on adapting to this hazard, refer to Section 5.2.7. on preferred materials for subsidence.

6.2.8. Primary structure

Drought-induced subsidence can damage a building's primary structure. **Strong and stable foundations** should be incorporated. For guidance on adapting foundations to drought-induced subsidence, refer to Section 5 on subsidence.

6.2.9. Services

Improving water efficiency is key to adapting buildings to periods of drought. **Installing water efficient and water-saving fixtures** and **fittings** within the building can reduce household water consumption. Examples include: **flow restrictors, delayed inlet valves** and **low-flush toilets.** Additionally, regular checking and fast remediation of leakages is crucial.

Greywater recycling systems can be considered an alternative water supply source for irrigation. A system can be installed that collects wastewater from showers, bathtubs and wash basins for use in toilets and washing machines, which then recycles it within the building for on-site use.

An **air-handling unit (AHU) condensate capture and reuse system** can also conserve water. As air passes across cold cooling coils in an AHU, it condenses on the coils. The water will collect and drop to the drain pan below, which can then be reused in the building.

6.2.10. Other

The measures described under Section 5 on subsidence are applicable when adapting to drought-induced subsidence.

6.3 Technical assessment, guidance & tools

Spain's Guide for Rainwater Collection (Guía Técnica de aprovechamineto de aguas pluviales) by AQUA ESPAÑA (2016) provides criteria and best practices for applying, installing, and maintaining rainwater collection systems. It is a particularly valuable for other Mediterranean and continental regions.

The Code for Sustainable Homes (UK), Category 2: Water provides details on the installation of rainwater harvesting in new builds.

EPA WaterSense at Work have produced Best Management Practices for Commercial and Institutional Facilities.

ASHRAE Green Guide: Design, Construction, and Operation of Sustainable Buildings chapter on water efficiency explores how heating, ventilation and air conditioning systems, water heating, plumbing design, and potential water recovery and reuse systems can contribute to green building designs

The Federal Energy Management Program (FEMP) and the U.S. Environmental Protection Agency (EPA) developed 14 water efficiency best management practices which can be publicly accessed online.

AECB Water Standard provides resources on individuals fittings with lowest water use for buildings. Good and best practice standards are detailed, and these allow users to use less water than predicted by the highest levels of the Code for Sustainable Homes.

PUB Singapore's National Water Agency's Best Practice Guide in Water Efficiency Buildings 2018 provides examples of best practice in implementing and managing water efficiency projects in buildings as well as water conservation in buildings, during dry weather.

Tools such as the Climate-ADAPT Water Scarcity Map Urban Adaptation Map enable viewers to prepare for future drought events as well as identify areas at risk to prioritise adaptive actions.

BREEAM International New Construction 2016 Technical Manual contains requirements for water consumption, monitoring, leak detection and prevention, and water efficient equipment within category 9.0 Water.

6.4 Case studies

ER2 Buildings in Arizona: The building addresses drought risks with water harvesting and green infrastructure featuring native and drought-tolerant plants. When it rains, the water falls to the courtyard, drips through balcony and terrace planters, and flows into catch basins before being collected in the 52,000-gallon (c. 240,000litre) holding and filtration tank installed underground. Landscaped beds are irrigated with the stored stormwater run-offs, captured building condensation, and reclaimed water.

Green facades in a retirement home in Madrid: The facade is using collected water from rain harvested systems to feed into the wall's irrigation. These systems collect and store water in two underground basins (Ayuntamiento de Madrid, 2019).

Carlton City Hotel Singapore: Water consumption is closely monitored in the building and there is a systematic fault-reporting system installed, as well as enforced daily inspections to prevent water wastage due to leakages. It also has water-efficient fittings in guest rooms and toilets. The hotel recovers AHU condensate and reuses it for the cooling tower. Carlton City Hotel Singapore has seen a drop of about 4233m^3 in water consumption from 2014 to 2016 (Singapore's National Water Agency, 2018).

Brock Environment Centre (USA): The building was initially projected to be able to store enough water to face a -23day drought but due to consumption being lower than foreseen, the building should withstand a longer period.

Bloomberg's European Headquarters in London: as part of its adaptation features the building has an on-site water treatment plant to collect and reuse rainwater from the roof, as well as greywater from sinks. In total, this results in annual water savings for 25 million litres. Overall, the building is 70% more water-efficient than a typical office building.

6.5 Industry actors

6.5.1. Government, regulators & local authorities

Public authorities play a crucial role in enabling easy access to information that can allow stakeholders to assess a drought-induced building's risk. Resources include **drought-risk maps** and **accurate weather predictions**, supported by **early warning systems**. Authorities can **identify** and **designate water-stressed areas.** This can support regulators in defining higher water efficiency standards in new developments, and encourage retrofitting in existing buildings.

Governments can encourage the **installation of water recycling systems by raising awareness and facilitating their implementation through funding**. For example, subsidies effectively encourage property owners to retrofit existing buildings for rainwater harvesting. In Krakow (PL), private water retention has been subsidized since 2014. In Wroclaw, residents can request an 80% reimbursement of the cost of installing rainwater collection systems (Kazmierczak et al., 2020).

Public authorities and decision-makers should refer to the European Commission's **guidance on integrating climate change adaptation in Environmental Impact Assessment (EIA) for droughts** (European Commission, 2021). A series of questions provided in Table 14 in the Commission Notice facilitate a thorough assessment of how proposed development could be adapted to droughts. Questions include 'Can the materials used during construction withstand higher temperatures?' and 'Will the proposed project increase water demand in the area?' This enables adaptation action from the outset. .

6.5.2. Investors, developers & insurance providers

Investors should identify the likelihood and impact of drought-related building hazards using **drought-risk maps.** Investors should then seek to understand the extent to which adaptation is incorporated in the potential investment portfolio, and evaluate the cost of adaptation measures. Depending on the level of drought-risk, developers may have to install the water efficiency and storage solutions described above, as well as measures to protect against subsidence risk.

6.5.3. Design teams (engineering and architecture)

Designers must ensure that **efficient water systems** are part of the design for new buildings and retrofitting existing buildings, to ensure they are more resilient to climate change. Measures to reduce water consumption and reuse greywater should be incorporated in all parts of the building.

Higher temperatures, lower precipitation, and a high risk of drought also affects the **design and location of water collection re-use and storage systems**. Designers should consider:

- the **location of collection systems:** these must be placed on a solid foundation;
- **exposure to sunlight**: the storage tank should be protected from UV light and heat (ideally buried and made of opaque material);
- the **size** - the volume of the storage tank should be defined by two factors: first, the demand generated by the system (i.e. utilities within the building). Secondly, the supply of water from the catchment surface and local rainfall patterns. The potential impact of more frequent and severe droughts on water demand and supplies should also be considered when sizing the water tank. This will ensure collection systems are resilient to future drought trends and the local rainfall patterns. Incorporating estimates of the droughts' impacts on water demand and supply is essential for adapting to more frequent and severe droughts.

Regulations and national building codes should be checked by designers when planning, sizing and detailing rainwater harvesting systems and water-efficient fittings in a development. Designers should aim to incorporate adaptation solutions to drought and drought-associated hazards in order to develop a holistic resilient building design.

6.5.4. Building users, facility managers and owners

Long-term water savings can be achieved by building users and owners implementing best practice water management in three main ways:

- **Reducing water loss and leaks**: leakages and burst pipes can disrupt water supplies, put extra pressure on water resources, and reduce water quality. Water loss compromises the resilience of a building's water supply during a drought, which may contribute to health and sanitation risks for building users. It is therefore essential that **regular maintenance, checks** and **repairs** take place, to identify leaks and monitor pipe pressure. Integrating sensors in the building that detect leakages quickly can help reduce their impact.
- **Increasing water effciency of fixtures:** Building users can reduce their drought-risk vulnerability by ensuring **efficient fixtures** are installed to help reduce water consumption. Before implementing water-efficiency measures, building owners must evaluate and understand water-usage patterns. This helps to identify the most appropriate measures for the building. The installation and use of **SMART measures** are critical tools, allowing building users to modify their behaviour patterns based on real-time information and providing an incentive to reduce water consumption
- **Reusing water onsite: rainwater harvesting systems** capture and store water for on-site use. Regular monitoring and maintenance of rainwater harvesting systems are required to ensure they function effectively. This can include **removing leaves** from the **roof** and **gutters**, regular **cleaning** and ensuring the **tank inlets and overflows exclude mosquitos.**

ADAPTING BUILDINGS TO WIDER CLIMATE RELATED HAZARDS

This section evaluates best practice building adaptation solutions for climate-related hazards identified in the EU Taxonomy. Priority hazards, i.e. those hazards that significantly impact a building and its users have been considered in the previous section.

The climate-related hazards evaluated here are:

Temperature-related hazards

- Wildfire
- Changing temperatures
- Heat stress
- Temperature variability
- Permafrost thawing
- Cold wave/ frost

Wind-related hazards

- Cyclone, hurricane, typhoon and tornado

Water-related hazards

- Changing precipitation patterns & types
- Precipitation & hydrological variability
- Sea-level rise
- Water stress
- Glacial lake outburst flood

Solid mass-related hazards

- Coastal erosion
- Soil degradation
- Soil erosion
- Solifuction
- Avalanche
- Landslide

7. Temperature - related hazards

7. Temperature - related hazards

7.1 Wildfire (acute)

Increasing high temperatures, combined with dry and windy conditions (also known as fire weather), increase the risk of wildfires (IPCC, 2021). Wildfires pose an increasing risk to buildings in parts of Europe, particularly in areas at the wildland-urban interface (WUI)

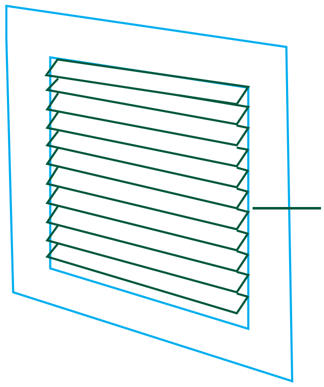
Protection against wildfires relies on **measures beyond the building's influence,** such as **raising awareness of the cause of wildfires**, **early monitoring** and **control**. However, adaptation measures can also be taken at the building level and should be considered if a risk is established.

Wildfires reach buildings by igniting materials via a direct flame, heat exposure or embers being blown by the wind. A **defensible zone** around the building **free of combustible materials** (such as trees, shrubs, timber sheds or timber terraces) can help provide protection against wildfires. Sufficient distance between buildings or sheds to prevent fire passing between buildings.

Similarly, **brush clearing** around the building reduces the density of vegetation. This can reduce the risk and prevent the fire from affecting the building. If a fire occurs, brush clearing can also reduce its intensity. **Brush clearing guidelines** may differ from area to area and therefore regional guidelines should be identified and followed if available. These measures are key as most buildings affected by wildfires are the result of insufficient brush clearing and vegetation planted too close to the building (Cordier & Prin-Derre, 2017).

Figure 43: Materials such as stone, tile, steel and concrete are less flammable than timber and plastics

Figure 44: Coverings of ventilation openings with screens or louvers prevent embers from entering



These adaptation measures result in trade-offs between some solutions for heat waves for which shading trees and green facades can improve indoor temperatures. Depending on the risk profile of a specific building, prioritisation and choice will therefore have to be made.

Wooden structures such as fences or paths should **not** be **connected** to the building. This measure also requires frequent **checks** and **maintenance** to prevent the build-up of dry leaves or needles in gutters or under steps.

Fire-resistant building compartments can reduce the fire spreading from flames, heat and embers. Through proper design, both **non-combustible materials** (such as stone, tile, steel and concrete) and **combustible materials** (such as timber and plastic) can help ensure the fire safety of buildings (Figure 43). Additionally, fire-resistance classifications can indicate the suitability of the material. Roofs and facades should not have gaps where debris can accumulate. Embers can start a fire in the building so should be kept outside. Ventilation openings are at high risk of letting embers ignite a fire in the building. **Ventilation inlets and outlets** should be covered with **metal screens** with small holes to avoid this situation (Figure 44).

High efficiency air filtration systems can reduce a building occupant's exposure to wildfire smoke. Building owners and managers should prepare to add supplemental filtration to the intake air vents of a building where possible, during smoke events. Various technologies are emerging; these include electronic, gas, fibrous media and mechanical filters. HEPA (high-efficiency particulate air/arresting) filters and electrostatic precipitators have been found to be the most effective methods in reducing exposure to wildfire-associated air pollutants (CDC, U.S., 2020 and Allen and Barn, 2020).

Available water can be used to irrigate trees and shrubs, as well as prevent other materials from igniting, so **storing rainwater** can be a useful precautionary measure.

Lastly, **emergency preparedness** of building residents and the knowledge of how to behave in the event of an approaching wildfire are important. Being prepared to quickly leave the building can save crucial time for residents and the emergency teams. Making sure all windows are closed and no easily combustible materials are left outside helps protect the building against the approaching fire.

7.2 Changing temperature (chronic)

Changing temperatures across Europe will contribute to risks associated with heat waves, cold waves and temperature variability.

The adaptation solutions described in Section 1: Heat waves are therefore applicable to changing temperatures.

7.3 Heat stress (chronic)

Heat stress combines the effects of high temperatures with dry conditions. Adaptation solutions described under heat waves and droughts mitigate heat stress as well. The key measures include:

- **shading of the building, particularly windows;**
- **reflective surfaces;**
- **insulation of all building parts;**
- **green roofs;**
- **ventilation that allows hot air to exit the building;**
- **rainwater harvest, storage and use for cooling effects.**

These are described in more detail in Section 1 (heat waves) and Section 6 (droughts).

7.4 Temperature variability (chronic)

Adapting buildings to temperature variations requires careful consideration of solutions to heat waves, cold waves and local climate conditions. The solutions presented in Section 1: heat waves and Section 7.5 Cold waves (below) are therefore relevant to temperature variability risks as well. Depending on climatic needs, adaptation solutions to droughts, winter storms and heavy precipitation may also be relevant. In particular, this includes:

- **insulation of the building;**
- **shading structures** or plants that allow for seasonal differences (see Figure 45);
- **passive and active ventilation** that can be adjusted to different outdoor temperatures.

Solutions like insulation provide adaptation benefits in all temperatures. Other solutions, such as building orientation and the size and direction of windows, are the exact opposites for heat and cold. In these cases, the most likely and more extreme hazards should determine the design and implementation of dominant adaptation solutions. **Adjustable installations** are ideal for other solutions such as shading devices or ventilation systems to maximise adaptation to varying temperatures. For example, r**emovable window shades or air outlets** that can be closed in cold periods allow greater flexibility for different conditions. Additionally, the effects of many **nature-based solutions** change with the seasons and enable all year adaptation. For instance, **deciduous trees** provide shading in summer but allow light to reach the building during winter as shown in Figure 45. Similarly, **green roofs** and **facades** create benefits for all temperature conditions as they insulate the building.

Structural elements exposed to temperature variations will have to be assessed for thermal expansion and shrinkage. If big temperature variations occur in large buildings, the frequency and position of movement joints needs to be considered. The primary structure may experience a large temperature variation during the construction period before insulation is added to the structure, resulting in additional movement joints needing to be considered.

Figure 45: Trees create seasonal adaptation effects. Deciduous trees allow sunlight to reach buildings in winter but can also provide shading in the summer.

7.5 Permafrost Thawing (chronic)

In the EU, permafrost soils cover very small parts of northern Sweden and Finland. The effects of thawing permafrost are closely comparable to subsidence. Thus, adaptation approaches for subsidence can also be appropriate to adapting to permafrost thawing for example:

- ensuring that **foundations** are **deep** enough to reach **stable ground;**
- **installing movement joints** to allow the building to resist and adapt to vertical and horizontal soil movement;
- installing a **peripheral drainage system** to keep moisture away from the foundations. More detail on adaptation solutions can be found in Section 5.

7.6 Cold wave / frost (acute)

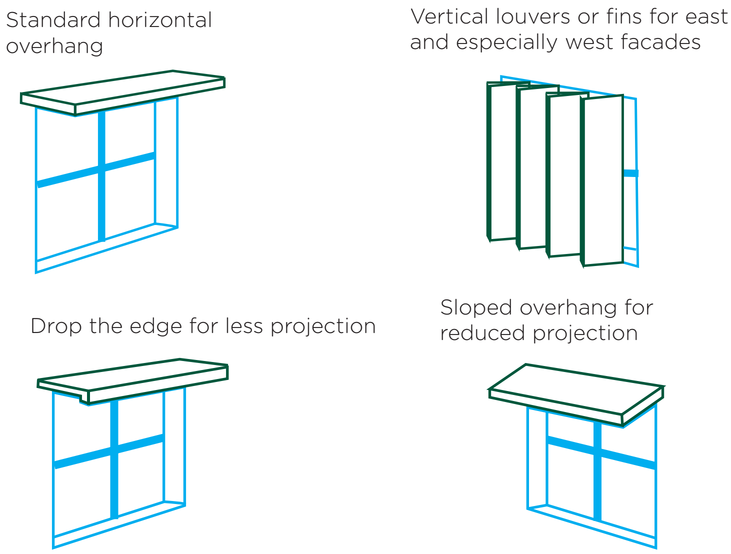
Many adaptation solutions for heatwaves can also be applied, in an adapted form, to cold waves and frost. An orientation towards the south is desirable for exposure to sunlight and the energy it carries.

Therefore, placing buildings on **south-facing slopes** and avoiding building in the shadow of other buildings is recommended for cold climates.

Insulation in the building, including walls, floors, and windows, helps maintain warm temperatures inside. Importantly, the insulation of the **roof** plays a central role (Figure 46).

As warm air rises, it may escape through the top of a building, while cold outside air pushes in.

Figure 46: Insulation helps maintain stable temperatures inside the building



Natural ventilation systems should be able to be **closed at ground** and **roof levels** and well managed to avoid heat losses through circulation while allowing for hygiene ventilation to maintain indoor air quality.

Thermal mass can store heat from sunlight during the day and release it at night or when temperatures decrease inside. During cold conditions, it is most effective to have the thermal mass exposed to sunlight during the day.

This ensures the highest heat gains and longest periods of re-radiation. This is the opposite of how thermal mass should be employed during heatwaves, where direct exposure to sunlight must be avoided.

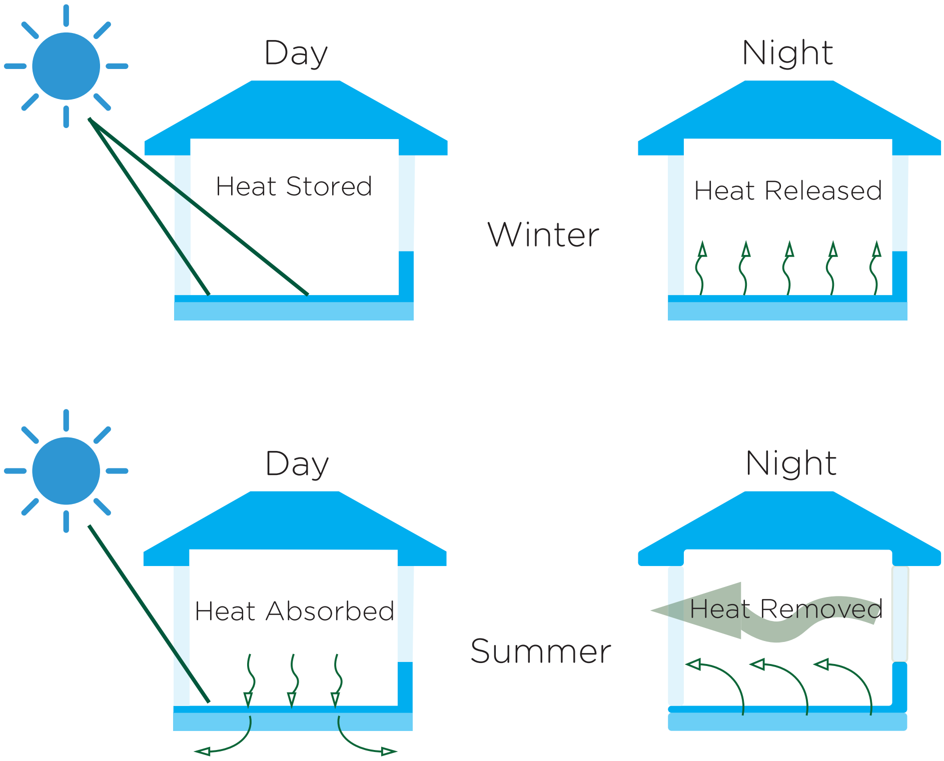
In buildings that are at risk of both heat and cold waves, **deciduous trees** or **shades over windows** allow winter sun to enter the building while protecting against the summer sun (Figure 45).

Temperature related hazards

Figure 47 illustrates the different effects of thermal mass in winter and summer.

The heat gain from sunlight can be increased through dark colours on external surfaces and large double/triple glazed windows in the direction of incoming sunlight. However, this solution should be applied carefully considering future climate conditions, otherwise the risk of overheating in summer and during heatwaves can be enhanced.

Figure 47: Thermal mass offers adaptation to cold waves as well as to heat



8. Wind related - hazards

8. Wind - related hazards

8.1 Changing wind patterns (chronic)

The Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report and interactive atlas found human-induced climate change to be decreasing average wind speeds across Europe, particularly in the Mediterranean region (IPCC 2021).

Severe windstorms are anticipated to increase (with a medium level of confidence). These changing wind speeds can influence evaporation, droughts, ocean currents, coastal sea-levels and wave patterns and fire weather (i.e.- a combination of hot, dry and windy conditions) (IPCC, 2021).

Severe windstorms can have devastating effects on poorly constructed buildings, distribution lines and transmission pylons (IPCC, 2022). A series of adaptation solutions are listed below as well as in Section 2.2, to support decision-makers in adapting the built environment to extreme winds-related events.

8.2 Cyclone, hurricane, typhoon and tornado (acute)

Intense storms have different names depending on where they originate and their wind speed. Cyclones, hurricanes and typhoons typically involve high winds, rainfall and storm surges. Hurricanes (forming over the North Atlantic, Central Pacific and eastern North Pacific) are the only storm-type to affect Europe.

A tornado is exclusive to land and usually made visible by a condensation funnel of water droplets, dust and debris. Tornadoes are often accompanied by hail (National Geographic, 2019). Therefore, solutions found in Section 2.2 (Storms), Section 3.2 (Heavy precipitation), and Section 4.2 (Flooding) apply.

The key feature of a building's resistance to acute storms is the roof (Section 2.2.5). When designing the structure of a roof, two aspects should be considered: geometry and stability.

- The best performing structure is a **squared roof with multiple panels, or a hip roof, with aerodynamic features designed to reduce wind forces** during an extreme wind event. Long overhangs or any type of roof protrusion should be avoided to reduce wind loads.
- Stability can be achieved with **gable cross-bracing and small openings to let some wind flow into the building**. In addition, r**oof fastening elements** should be frequent and preferably attached with screws instead of nails. In acute storms, **hurricane straps** help fasten the roof to the walls (see Figure 48).

Under the roof, sub-roofing and **strong sheathing** will provide an extra layer of protection against the forces generated by the wind.

Property damage can be significantly reduced by installing **impact resistant materials,** including **resistant glazing** (see Figure 50) and **tiles**, or **abrasive surfaces** that will soften the blow.

Figure 48: Hurricane straps can help fasten the roof to the walls

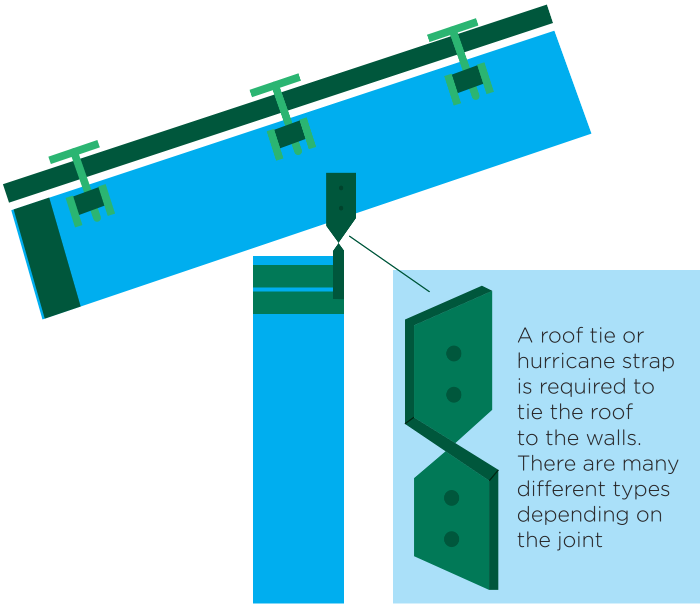
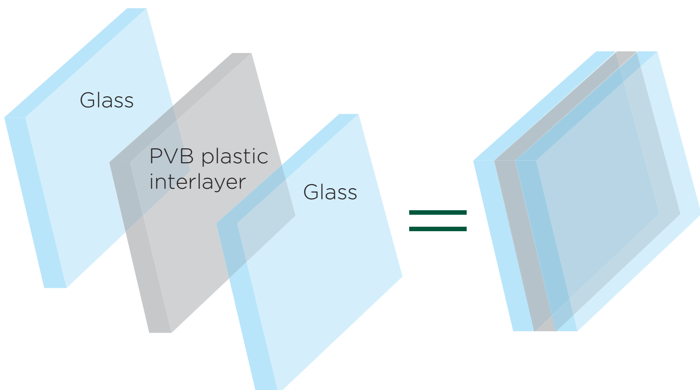


Figure 49: Impact-resistance glass helps prevent damage to windows



Wind - related hazards

Fragile elements of the envelope can be protected with a hail net. **Windows** should be **well sealed** and protected from the inside by a secondary defence and by **storm shutters** on the outside. Other openings should be secured and reinforced. Around the roof, **drainage systems** should be sufficient and **well maintained** to prevent issues such as water leakages.

The shape of the building also has a vital role in wind resistance (see Section 2.2.1). A **round, aerodynamic shape** would be favoured for all buildings. However, as most are not, **multiplying angles** will help reduce the wind load. Exterior glazing damage is very common during hurricanes and tornadoes **impact-resistant windows** that are well-sealed and protected from the inside by a secondary defence, and the outside by storm shutters is recommended. Other openings should be secured and reinforced.

Outside the building, **covered terraces, verandas,** and **patios** should have a **physical discontinuity** with the roof to prevent uplift damages. Furthermore, the **surrounding vegetation** should be chosen wisely to act as **windbreaks** and avoid causing harm (see Section 2.2.6). **Outdoor furniture** should also be **fixed** to the ground (see Section 2.2.8).

Finally, buildings should have procedures to anticipate episodes of violent winds and **built-in water storage** and **energy backup generators** (see Section 2.2.10).

9. Water - related hazards

9. Water - related hazards

9.1 Changing precipitation patterns and types (rain, hail, snow/ice)

The change in precipitation patterns and types due to climate change varies per region so it is important to assess what the expected impact is for each area. Various tools are available to identify future precipitation impacts, per country. These include the Taloen tool for France, the Klimawandel und Starkregen tool in Germany and klimaateffectatlas.nl for the Netherlands.

The solutions to changing precipitation patterns resulting in longer or more intensive heavy rainfall and accumulation of snow or ice are similar to the solutions to heavy precipitation. These include:

- **green, blue-green or blue roofs that can store water;**
- **use of water-repellent materials and seals in the basement and ground floor to prevent impact from pluvial floods;**
- **elevated entrances;**
- **permeable ground surface such as green gardens and gravel to increase infiltration rates;**
- **green facades;**
- **hail-proof window blinds;**
- **gutter and downspout maintenance and connection to water-storage solution.**

More information on the specifics of each solution can be found in Section 2 on heavy precipitation.

A change in precipitation pattern can also mean longer periods of drought followed by longer periods of flood risk. Drought can cause soil shrinkage and movement as a consequence of falling groundwater tables.

Solutions to subsidence associated impacts are:

- **deeper foundations;**
- **structural strengthening of walls;**
- **management of vegetation around the building (such as root barriers);**
- **installation of a peripheral drainage system to keep moisture away from the foundations;**
- use of **flexible jointed pipework** and **flexible seals** at the fitting to prevent leaks. More information can be found in Section 6 on subsidence.

Pro-longed periods of flood can require the building to be dry proofed. This will prevent any water from entering the building in the event of a flood. **Flood barriers** such as **elevated steps** and **entrances** or **highwater garage entrance barriers** can be an effective way to minimise damage. For foundations, **stilts** can be used to elevate the ground floor above the flood level. For new buildings, a waterproof layer can be applied to outside walls, preferably during the construction phase. For further details, see Section 4 (Flooding).

9.2 Precipitation and/or hydrological variability

Hydrological variability can cause subsidence and/or flooding. Floods and droughts are more likely to happen consecutively within a given region, due to climate change (EEA, 2018). This means buildings should be prepared against both hazards; also solutions against flooding should be compatible with solutions against drought. Even though the impacts of flood and droughts on a building differ, some solutions are similar. For example, **deep and water-resistant foundations** are applicable against floods and droughts.

Some adaptation solutions are not similar, but can be compatible. For example, flooding can damage building services if overflow water enters the building through sewage pipes. Solutions include an **anti-return valve** and reducing the amount of water in the sewage by, for example, **disconnecting downspouts.** Drought has an impact on pipes due to subsidence. Solutions include **flexible jointed pipework** and **flexible seals**. These solutions can co-exist.

For water retention, increasing the amount of vegetation around the building is suggested. **Vegetation increases the infiltration rate** and can help to reduce the amount of floodwater. However, for droughts vegetation, particularly tree roots can cause soils desiccation close to the foundations creating a risk for subsidence especially for subsidence-prone soils such as clays. Ensuring tree roots are not close to the building can reduce this risk.

9.3 Sea-level rise

Sea-level rise is a particular risk for coastal cities. A rise in sea-level for low-lying coasts causes more frequent or intense extreme flooding, enhanced erosion and salinisation of soils, ground and surface water. Adaptation solutions against long-term flood prevention and sea-level rise are described in Section 4 (Flooding) and Section 5 (Subsidence). These include:

- foundations in areas prone to coastal flooding should be designed considering all forces resulting from wave action, debris impact, erosion and local scour. The use of **deep foundations** is recommended, for example using stilts or pillars as a foundation above the flood level;
- **using saltwater-damage-resistant materials** for the primary structure in order to resist the conditions;;
- **Eelevating etrances and essential functions** above the **flood level**. The flood level to consider at the design tage should include the mutual effect of sea-level rise and storm surges;
- locating buildings, especially those providing critical functions, on higher ground.

9.4 Water stress

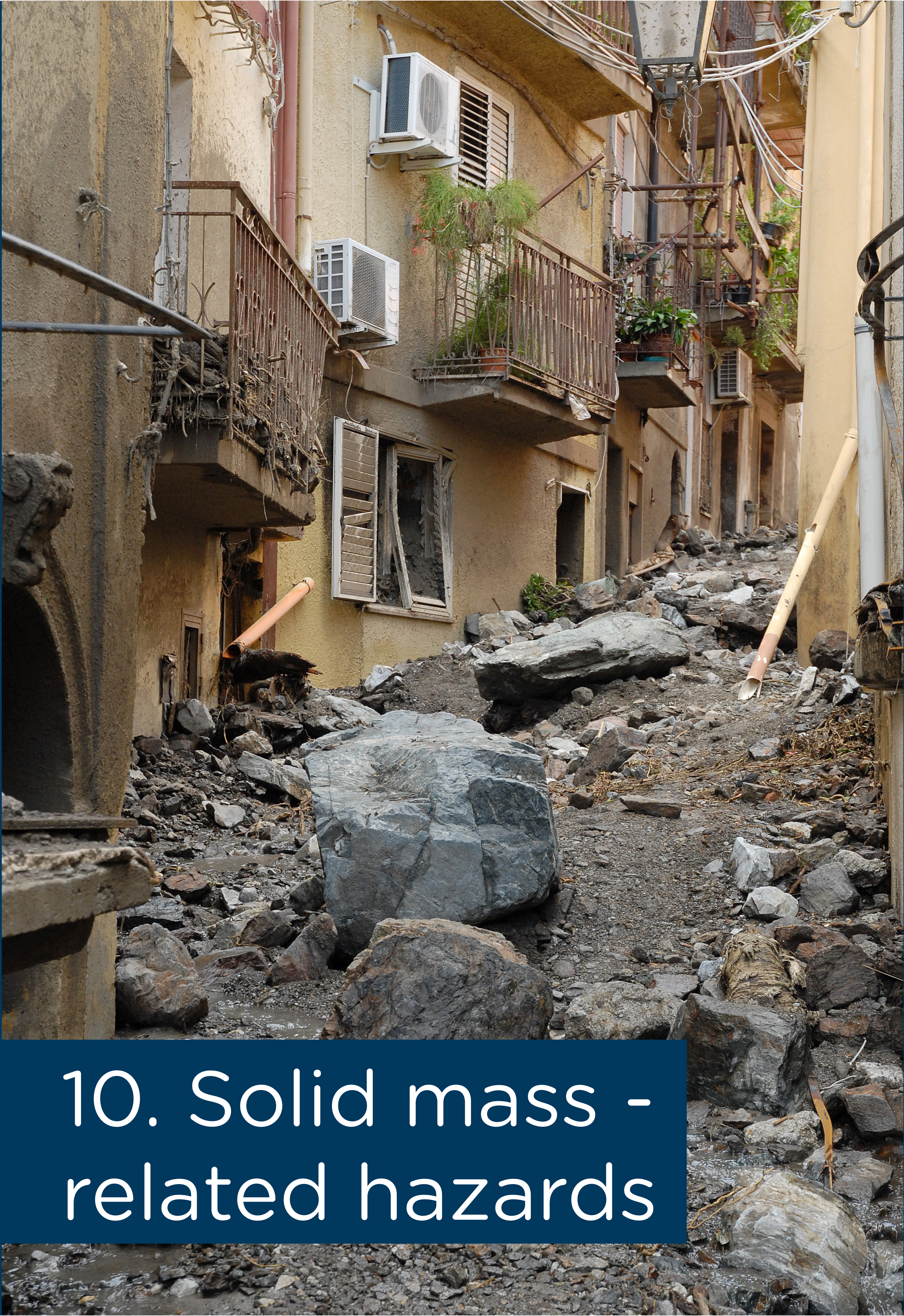
Water stress can refer to reduced fresh water resources in terms of quantity (caused by drought) or quality (caused by pollution or flood-induced contamination) (EEA, 1999). Adaptable measures to prevent water stress focus on water storage. The solutions within Section 3 (Heavy precipitation) and Section 6 (Drought) are therefore relevant. These include storage solutions for rainwater and the use of nature-based solutions:

- **Harvest rainwater from roofs** and **store in rain barrels or underground water storage tanks** via a connection from the downspout;
- The use of **blue-green infrastructure and sustainable drainage systems (SuDS)** such as swales and rills around the building space is an effective way to accommodate water for short durations;
- **Planting** of appropriate species that are drought-tolerant such as succulent plants and grasses;
- **Green roofs and infiltration trenches.**

9.5 Glacial lake outburst (acute)

This hazard is particularly relevant to alpine regions in Europe. Lake outbursts of any kind are very destructive to buildings, and more importantly, the lives of residents. The most important adaptation solutions are the **continuous monitoring** and **measurement** of **lake outburst risk,** and the implementation of an **early warning system** within high-risk areas

10. Solid mass - related hazards



10. Solid mass - related hazards

10.1 Coastal erosion (acute)

Coastal erosion is the process by which local sea-level rise, strong wave action, and coastal flooding wear down or carry away rocks, soil, and/or sands along the coast.

Erosion processes have increased as a result of rising sea-levels, increasing temperatures and storm surges. Buildings located on the coastline are vulnerable to coastal erosion, which causes structural instability.

Best practice adaptation approaches for buildings exposed to coastal erosion are grouped into three main approaches (see Figure 50):

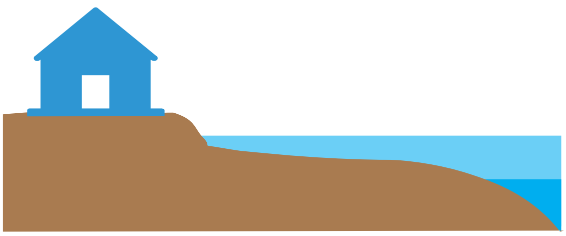
Figure 50: Overview of coastal erosion adaptation approaches for the built environment

Protect

Protect coastal development e.g. seawalls, dikes, beach nourishment, sand dunes, surge barriers, land claim

Accommodate

Regulate building development and increase awareness of hazards, e.g. flood-proofing, flood hazard maps, flood warnings



Retreat

Establish building setback codes e.g. managed realignment, coastal setbacks

1. Protection:

Structural interventions / shoreline hardening approaches involve the implementation of hard defence structures (seawalls, groynes, detached breakwaters, riprap, and levees).

Soft protection approaches involve **beach nourishment** and **coastal vegetation restoration.** Beach nourishment is a non-structural stabilisation technique that collects replacement sand inland and transports it to the coast. Coastal vegetation restoration encourages the growth of salt marshes, mangroves, and seagrasses adapted to the coastal environment. Any species selected must have dense and deep roots (such as roses, raspberries, etc.) to will help retain sediments. Extensive **monitoring of sand redistribution** following soft protection approaches is crucial to assess the projects performance and impacts.

These defence approaches are vulnerable to damage from storm and wave action, but help prevent overtopping inundation and continued erosion. Furthermore, the residual risk remains due to climate change resulting in a more extreme climate.

2. Accommodation:

Communities continue to occupy buildings in vulnerable areas that are then adapted to flooding and erosion. Buildings in areas at risk of coastal flooding should implement flooding adaptation approaches identified in Section 4. **Stilts** or **pillars** may be used to flood proof building foundations, **Water** and **salt-water resistant materials** may be used to floodproof the primary structure). Accommodation also involves using **information systems** (such as **flood hazard mapping, soil surveys,** and **early warning systems)** to minimise the impact of flood events. These approaches however may loose their effectiveness over time and must therefore be reviewed regularly.

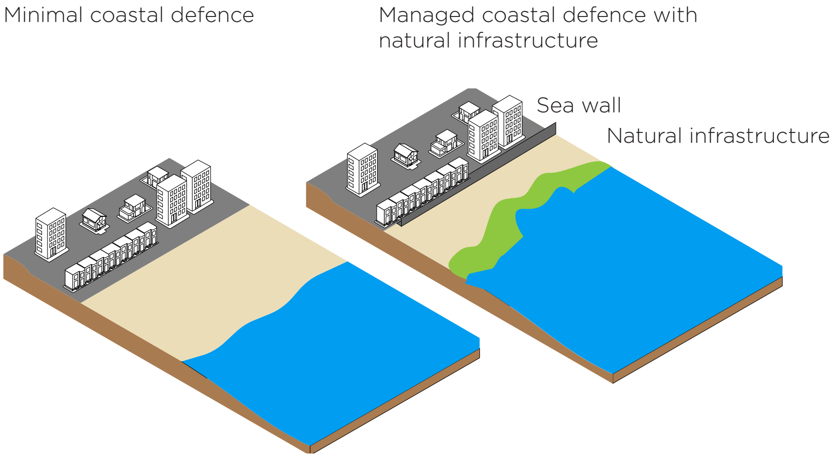
3. Retreat:

Planned actions can be taken to move buildings and people away from coastal erosion hazard areas. Building-a specific retreat approach involves **designating an area set back** and defining a **buffer of minimum distance** or **elevation** between areas of coastal erosion and buildings.

On a wider scale, a combination of installing **coastal defences** and allowing an **intertidal environment** (or **natural infrastructure**) to develop can reduce the risk associated with coastal erosion and flooding. The intertidal habitat acts as a buffer, providing greater flood protection and can enhance biodiversity. Figure 51 illustrates how this can protect buildings from coastal erosion.

European coasts are increasingly vulnerable to coastal erosion due to sea-level rise. One of the most vulnerable is the Portuguese coastline, and adaptive approaches have included **relocating buildings** and **resettling communities** (Clima-ADAPT, 2016).

Figure 51: Managed coastal defence (Diagram adapted from Sutton-Grier, et al., 2015).



Spain's coast is also vulnerable to soil erosion and its adaptation strategy identifies accommodation (by adapting buildings designs and using flooding resilient materials) and retreat (e.g. management realignment, including buying land to implement nature-based solutions and retreat approaches) (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2016).

An **effective local planning system** is crucial for developing best practice adaptation pathways for buildings; a long-term planning system should seek to support the transition of buildings from high-risk land and restricts future development in areas affected by coastal erosion.

Monitoring tools and **flood risk models** for informal coastal management and adaptation will be crucial to assist local authorities, design teams, owners, buildings users, and investors. For example, the British Geological Survey has developed **GeoCoast** (British Geological Survey, n.d.), a data product that informs and assists users when responding to coastal adaptation and resilience.

It includes information about coastal erosion, sea-level rise and inundation, coastal subsidence and the properties of geological deposits. Understanding the risk allows stakeholders to implement the appropriate adaptation measures.

10.2 Soil degradation (acute)

Soil degradation is a natural process. However it has been exacerbated by anthropogenic activities and climate change (Montarella, 2007). Soil degradation reduces the soil's ability to absorb and filter water. This can lead to drought, loss of soil structure and flooding due to increased water run off during heavy precipitation events.

Soil degradation poses a particular risk to a building's foundations, increasing the likelihood of erosion or soil displacement.

Building adaptation approaches to reduce vulnerability to soil degradation overlap with those presented in Sections 4.2 (Flooding), 5.2 (Subsidence) and 6.2 (Drought). Conducting a **preliminary soil study** to evaluate whether the soil is susceptible to degradation is an important initial step prior to selecting a location for construction a building.

10.3 Soil erosion (acute)

Soil erosion is the accelerated loss or degradation of topsoil, often associated with climatic effects such as strong winds, heavy rainfall and thunderstorms. Poor land management can further exacerbate soil erosion (Sivakumar and Stefanski, 2007).

During the construction phase, effective soil quality management is crucial as this is when the site is most vulnerable to soil erosion. Measures can include re-vegetating and increasing soil organic matter levels to re-mediate the on-site damage caused by site preparation (United States Department of Agriculture, 2000).

Building design elements to adapt to and mitigate against soil erosion include:

- **installing drains** and **gutters** to effectively channel rainwater away from building foundations
- **planting grasses** and **flowers** around building foundations. Their roots will help anchor the soil in place and reduce soil loss (URETEK, 2019).

10.4 Solifluction (acute)

Solifluction is the slow, steady flow of water-saturated soil down a steep slope. This movement of soil is attributed to freeze-thaw cycles that induce downslope movement, particularly in periglacial climate conditions and cold environments. Land slippage and mudflows associated with solifluction pose a threat to buildings.

As with other mass-movement related hazards, adaptation measures focus on an **initial hazard assessment** and the **selection of a location that minimises the risk** of solifluction.

For existing buildings, adaptation measures involve **maintaining** and s**trengthening the building structure's stability.**

10.5 Avalanche (chronic)

Snow avalanches are fast-moving snow mass movements that move downwards and occur within mountain environments. Avalanches pose three major threats to buildings:

- high pressure loads and suction effects from the avalanche can impact the walls and roof of a building
- the impact of of snow loads, solid earth, or rocks and rubble that are transported with the avalanche can threaten the stability of a building
- snow and ground can cause internal damage if it enters (with force) via the building openings.

Avoiding at-risk areas should be a priority for all new construction. It may be possible to adapt existing buildings with constructional and design elements to resist the impact forces of snow avalanches and associated fluvial sediment transport. Best practice designs for adapting residential buildings include the following (Holub, Suda and Fuchs, 2012):

- basements should be **waterproofed** with **correct detailing** and could use **water-resistant concrete;**
- **external avalanche walls** should be either retrofitted (e.g., by an additional shell) or constructed from materials such as stone or concrete;
- **building openings should be avoided on the process-oriented (impacted) building walls;**
- **openings at ground surface level should be eliminated;**
- if necessary, specially **reinforced multilayer window glass, window frames** and **fittings** are available to protect against the considerable impact pressure of avalanches.

Defence structures beyond the building structure for deviating, braking and containing avalanches are crucial particularly where there are existing buildings in exposed areas with traditional masonry that do not have high resistance (MAIF, 2022). **Protection approaches such as snow bridges, snow rakes and nets** around the surrounding area of the building can help prevent damage.

10.6 Landslide (chronic)

Landslides are a gravitational mass movement of rock, debris, earth or mud down a slope. They pose a severe risk as buildings may become buried, filled with landslide deposit, deformed or compromised, destabilised and vulnerable to collapse. Landslides are frequently triggered by heavy rainfall and earthquakes. Changes in precipitation and temperature levels can alter the slope and bedrock stability,, which may also trigger a landslide.

Hazard or **risk assessment** and **monitoring** is the initial step for landslide building adaptation. **Geological data** derived from **geological maps, existing boreholes** or **risk mapping** allows stakeholders to identify the most susceptible areas. This information can then support the implementation of contextually specific adaptation measures.

There are several good examples of publicly available **landslide risk maps**. **Ro-RISK** (Ro-Risk, 2017), was developed in Romania with EU funding. Landslide risk hazard maps were developed by correlating historical rainfall and historical landslide events. The GFDRR produced **Think Hazard!,** a global open-source hazard map for landslides and other hazards (GFDRR, n.d.). Swedish authorities produce map data for analyses of conditions for collapse, landslides and erosion (Statens geotekniska institute, n.d.). These are valuable tools for adaptation processes and planning.

Land use planning and designated 'no build' areas are the most effective in reducing the risks of landslides. In Switzerland, land-use planning is used to define risk zones. These are categorised into three zones: red - building is strictly prohibited; blue - building is possible, but designs must include adaptation; and yellow - no building restrictions (Raetzo et al., 2002).

Superficial landslides (those that occur within 2m of the ground surface level) are best resolved by performing **stabilisation work** around the building. However, for deeper landslides, greater building protection and **reinforcement** measures are required.

Professional advice from geotechnical engineers should be sought to avoid building in landslide prone areas and understand which adaptation approaches are best suited.

Landslide mitigation measures may include (LaRiMiT, 2016):

- erosion control measures (geotextiles, rip rap, turfing);
- modifying slope geometry;
- surface and groundwater drainage works such as sub-horizontal drains and vertical wells;
- modifying the mechanical characteristics of unstable mass (compaction, jetting, cementitious grouting);
- mechanical transfer of loads to more competent strata (soil nailing, caissons, strand anchors);
- retaining structures to improve slope stability (stem walls, gabion, crib walls);
- passive controls for deviating landslide (baffles, deflection structures, barriers).

Careful consideration of the location of these measures is required, to ensure they protect the largest area possible and decrease the probability of an avulsion.

Appendix A

Building solutions by priority hazard

Possible solutions to adapt buildings to the priority hazards are summarised in the tables on the following pages. They are listed by Hazard, in order of cost (low to high) and ease of implementation (simple to complex). Each adaptation will have a beneficial impact, improving a building's capacity to respond to the target hazard. However, the adaptation may also create an indirect effect, with a potentially negative impact on the building's capacity to respond to other hazards. These interactions are highlighted in the table below.

Legend:

	Solution has a beneficial impact in responding to this hazard
	Solution has an indirect beneficial impact in responding to this hazard
	Solution has a negative impact on this hazard if implemented
	Not relevant / no interaction

Careful consideration is required when identifying appropriate solutions for both new and existing buildings. For detailed strategies, tailored to specific building types or environmental locations, appropriate professional guidance should be sought to ensure adaptations are effective against climate change.

Heat waves

Solution	Category	Cost	Ease of implementation	Heat waves	Storms	Heavy precipt.	Flooding	Subsidence	Drought	Commentary on co-benefits	Commentary on negative impacts
Exterior shading	Building shape	LOW	SIMPLE							• Limits solar gains by reducing the entry of sunlight and heat into the building. • Reduces energy demand for cooling.	• Elements that protrude from the building's structure are at risk of uplift from high winds. • Trees used to create shade should be carefully selected to avoid them being uprooted during storms (causing damage).
Green roofs	Roof	LOW	SIMPLE							• Can support biodiversity. • Can provide significant noise reduction. • PVs can be combined with a green roof; vegetation can reduce the surrounding temperature and improve PV efficiency.	• Increases the amount of material required in structural elements, resulting in higher embodied carbon. The depth of substrate can be reduced in conjunction with suitable planting to reduce the load.
High vegetation on sun-exposed sides of the building	Vegetation	LOW	SIMPLE							• Reduces energy demand for cooling. • Beneficial for local biodiversity. • Increases water uptake of soil.	• There is a risk of vegetation being uprooted during storms and flooding and causing damage. • If the roots are too close to the building foundations they can increase vulnerability to subsidence.
Night ventilation	Services	LOW	SIMPLE							• Reduces energy demand for cooling and ventilation	• If applied to parts of the building below flood level, damage can arise in the event of a flood.
Use of energy-efficient appliances in the building	Services	LOW	SIMPLE							• Reduces energy demand for cooling and ventilation.	• No negative climate adaptation impacts have been noted.
Active cooling and ventilation appropriate to the building's needs	Services	LOW	SIMPLE							• Provides immediate cooling in periods of extreme heat • Can provide further relief when passive ventilation measures are no longer efficient.	• Higher energy consumption than passive cooling solutions. • Standing water as an effect of flooding might damage the electrical components of outdoor active cooling units. • Driving rain may cause damage when dirt and debris enter the unit.
Enable passive airflow through the building for ventilation	Space consideration	LOW	SIMPLE							• Reduces energy needed for cooling and ventilation.	• There may be instances during the year where internal temperatures may become high unless active mechanical cooling is used.
Light-coloured and reflective materials on roofs, walls, windows and blinds	Walls	LOW	SIMPLE							• Limits solar gains by reducing the entry of sunlight and heat into the building.	• Risk of creating a glare effect. High albedo coatings can be dazzling and cause daily discomfort for people on the exterior of the building. • High reflection rates can intensify light pollution and disturb local biodiversity.
Thermal mass	Preferred materials	LOW	MODERATE							• Reduces energy needed for heating and cooling. • High thermal mass materials are an inherent feature of some heritage buildings.	• Exposed thermal mass can leave hard surfaces that negatively impact the acoustic quality of the space.

Building solutions, by priority hazard

Heat waves

Solution	Category	Cost	Ease of implementation	Heat waves	Storms	Heavy precipt.	Flooding	Subsidence	Drought	Commentary on co-benefits	Commentary on negative impacts
Passive ventilation through thermal chimneys	Space consideration	LOW	MODERATE							• Reduces energy demand for cooling and ventilation.	• No negative climate adaptation impacts have been noted
Green facades	Walls	LOW	MODERATE							• Reduces energy demand for cooling. • Supports local biodiversity. • Enhances infiltration rates of soil (in the case of a ground-rooted facade).	• Green facades have an ongoing maintenance and cost • Humidity casused by a wall structure can be harmful to the thermal function or integrity of the wall. Potential for mould growth.
Insulation of walls, windows, and roofs	Walls	LOW	MODERATE							• Reduces the energy needed for heating and cooling. • Possibility to reduce embodied carbon by using bio-based materials.	• Insulation materials may not be water resistant; increases risk if exposed to water (e.g. flooding). • Possibility of humidity occurring within the walls and roof should be considered; humidity management measures may need to be implemented
Reduce facade glass surface in direction of sunlight	Walls	MEDIUM	SIMPLE							• Reduces the energy needed for cooling.	• Trade-offs with natural lighting and desired heat gains during winter.
Increase use of protective surface coatings/or alkali-activated cement	Materials	MEDIUM	SIMPLE							• Increases durability of the structure and reduces reinforcement corrosion.	• Additional material required; associated increase in embodied carbon.
Building orientation away from direct sunlight to control solar gains	Building shape	MEDIUM	MODERATE							• Reduces the energy needed for cooling.	• Potential trade-offs with natural lighting and desired heat gains during winter
Photovoltaic installations on the roof	Roof	MEDIUM	MODERATE							• Photovoltaics (PVs) can act as a shading device to a roof to limit heat gains and reduce the cooling load. • PVs can be combined with a green roof; surrounding vegetation can reduce the temperature and improve PV efficiency.	• PV on roofs should be impact-resistant in storm and hail-prone regions. • The installation of PV on roofs competes with space for intensive green roofs that contribute to biodiversity (unless shade-resistant plants are placed underneath). • In the event of a fire, electrical hazards and combustible components can increase the spread of flames. • Ballasted PV systems can be heavy resulting in an increase of structural material required. Where applicable lightweight PV systems can be used instead
Roof overhangs, verandas, and patio roofs	Roof	MEDIUM	MODERATE							• Reduces the energy needed for cooling.	• During instances of high winds, long protrusions are considered as fragile elements of a building
Use of phase change material technology for storing heat to release at night	Preferred materials	MEDIUM	MODERATE							• Reduces the energy needed for heating and cooling	• Phase change material can be combustible and therefore increase the spread of flame risk
Temperature zones within a building by avoiding flow of heated air	Space consideration	MEDIUM	MODERATE							• Reduces the energy needed for cooling	• Potential trade-offs with natural lighting and desired heat gains during winter
Connection to district cooling	Services	MEDIUM	COMPLEX							• Benefits from a higher energy efficiency of centralised cooling sources.	• District systems require master planning and a high level of coordination. • Mechanical ventilation my be required to ensure adequate air exchange
Evaporation cooling as part of ventilation/airflow	Services	MEDIUM	COMPLEX							• Reduces the energy needed for cooling	• Higher water consumption • Management of humidity may be needed.
Movement joints	Structure	MEDIUM	COMPLEX							• Protects buildings against the possibility of cracking as a result of high temperature variability	• Important consideration at the construction stage (before the structure is thermally insulated).
Geo-cooling	Services	HIGH	COMPLEX							• Provision of renewable energy source	• No negative climate adaptation impacts have been noted.

Building solutions, by priority hazard

Storms

Solution	Category	Cost	Ease of Implementation	Heat waves	Storms	Heavy Precipt.	Flooding	Subsidence	Drought	Commentary on co-benefits	Commentary on negative impacts
Changing the size and increasing the frequency of fastenings for roof tiles, slates, and ridges.	Roof	LOW	SIMPLE							• Prevents roofs from being wholly or partly uplifted from a building's structure during high winds. • Prevents roof damage due to heavy precipitation/load • Screws, rather than nails, and large washers are recommended.	• No negative climate adaptation impacts have been noted.
Effective roof drainage system	Roof	LOW	SIMPLE							• Prevents water pooling and leakage into building interior (and potential mould growth). • Prevents concentrated snow loads at the eaves.	• No negative climate adaptation impacts have been noted.
Hip-roof (with slopes of 30 degrees)	Roof	LOW	SIMPLE							• Hip-roofs with slopes of 30 ° have the best results in resisting strong winds and help shed snow most easily. • Gutters can easily be installed on hipped roofs. • This shape also improves ventilation.	• Sloped roof design limits opportunities for other adaptation solutions. Roof design may conflict with design aesthetic or cultural value of the building.
Hurricane straps and clips to fasten the roof to the walls	Roof	LOW	SIMPLE							• Under the roof, the linkage between the roof and the walls should be reinforced to prevent uplift.	• No negative climate adaptation impacts have been noted.
Lightning rods / air terminals	Roof	LOW	SIMPLE							• Lightning rods, or air terminals, can redirect electrical currents from lightning to the ground (reducing risk of fires and power surges).	• Lightning rods have a voltage limit and sometimes cannot divert all the energy
Physical non-continuity between the roof of the building and an extension (covered terrace, veranda, patio)	Roof	LOW	SIMPLE							• Prevents damage to the main roof if the extension is damaged or carried away by high winds.	• No negative climate adaptation impacts have been noted.
Short overhangs and protrusions	Roof	LOW	SIMPLE							• Long overhangs or any type of roof protrusion should be avoided to reduce wind loads.	• Reduces the extent of shading provided by the roof (and protection from overheating in high temperatures).
Favour hedges and shrubs over trees around the building	Vegetation	LOW	SIMPLE							• Vegetation can act as a windbreak offering some level of protection in the event of storms. • Trees should be placed at a safe distance from the building.	• Reduces the extent of shading provided by taller trees (and protection from overheating in high temperatures).
Surge protection device	Services	LOW	SIMPLE							• Can prevent power surges (caused by lightning) causing damage to electronic devices.	• No negative climate adaptation impacts have been noted.
Fix outdoor furniture and slabs to the ground	Space consideration	LOW	SIMPLE							• Prevents uplift and damage to furniture, slabs and terraces.	• Once anchored in place, outdoor furniture cannot be moved easily, reducing the flexible use of outdoor space around the building.
Sealant joint in windows	Windows	LOW	SIMPLE							• Careful design and sealing will prevent moisture and water from entering the building. Improves insulation of building and reduces likelihood of mould growth.	• No negative climate adaptation impacts have been noted.
Storm hooks to secure openings	Windows	LOW	SIMPLE							• Protects doors and windows from bending inwards in strong gusts of wind.	• Additional solutions are required to ensure protection from storms. Not the most effective as a standalone solution.
Impact resistant shingles	Roof & preferred material	LOW	MODERATE							• Minimises roof damage during severe weather events	• Shingles have a shorter design life than tiles. • Shingles may conflict with the aesthetic design and cultural value of the building.
Strong connections between exterior building elements (roof-walls, walls-foundations, foundations-ground)	Walls	LOW	MODERATE							• Improves structural strength of the building to resist wind forces.	• No negative climate adaptation impacts have been noted.
Favour aerodynamic shapes	Building shape	LOW	COMPLEX							• Reduces wind resistance on the building structure. • These shapes can also be earthquake resistant. • A round shape will also allow the inside to have constant natural light.	• Precise design and engineering required for curved walls and windows increases capital building costs significantly
Sub-roofing and sheathing to reinforce the roof	Roof	MEDIUM	SIMPLE							• Increases structural resilience of roof. • Sheathing also provides an additional barrier to prevent leaks.	• No negative climate adaptation impacts have been noted.

Building solutions, by priority hazard

Storms

Solution	Category	Cost	Ease of Implementation	Heat waves	Storms	Heavy Precipt.	Flooding	Subsidence	Drought	Commentary on co-benefits	Commentary on negative impacts
Lower friction roof surfaces such as steel roofs and standing seam roofs	Roof & preferred material	MEDIUM	SIMPLE							• Metal roofs have a longer life expectancy than traditional roofing material. • Natural coloured metal roofs reflect thermal radiation which can reduce building cooling costs (if combined with adequate roof insulation).	• No negative climate adaptation impacts have been noted.
Sheathing to reinforce walls	Walls	MEDIUM	SIMPLE							• Exterior wall sheathing strengthens the wall system, provides a nailing base for the siding, and gives a layer of protection against outside elements	• Most structural exterior wall sheathings lack insulation value
Cross-bracing	Roof	MEDIUM	MODERATE							• Reinforces the structure of a roof, reducing risk of damage in the event of storms or earthquakes	• Flexibility of a space may be compromised by cross bracing.
Impact-resistant solar panels	Roof & preferred material	MEDIUM	MODERATE							• Impact-resistant solar panels reduces the risk of damage from hail and debris during storm events. • PVs can act as a shading device to a roof, reducing the heat gains of a building.	• The installation of PV on roofs competes with space for intensive green roofs • In the event of a fire, electrical hazards and combustible components can increase the spread of flames.
Burial of distribution lines	Services	MEDIUM	MODERATE							• Avoids power or utility network disruptions in high winds or storm events.	• No negative climate adaptation impacts have been noted.
Rainscreen cladding systems	Walls	MEDIUM	MODERATE							• Prevents deterioration of outside walls (reduced maintenance costs). • Improves thermal performance of the building	• No negative climate adaptation impacts have been noted.
Secondary protection in walls for wind-driven rain	Walls	MEDIUM	MODERATE							• A vapour barrier may be cheaper to install than a drainage system.	• May impact the passive ventilation of building. An expert should evaluate the ventilation systems before installing vapour barriers.
Reinforcement and protection of openings, storm shutters	Walls & windows	MEDIUM	MODERATE							• Prevents high winds and airborne debris from entering the building and creating wind pressure inside. • Shutters can be used in high temperatures to reduce internal building temperatures by limiting the entry of sunlight and heat into the building.	• Permanent shutters may conflict with an aesthetic design and the cultural value of the building.
Impact-resistant glass for windows and doors	Windows	MEDIUM	MODERATE							• Helps to prevent air entering the building that could otherwise create a change in pressure, which could lead to walls becoming overstressed or roof uplift.	• No negative climate adaptation impacts have been noted.
Installation of backup generators	Services	HIGH	MODERATE							• Enables building to continue operating even if power supplies are interrupted by high winds and storm events.	• No negative climate adaptation impacts have been noted.

Building solutions, by priority hazard

Heavy precipitation

Solution	Category	Cost	Ease of Implementation	Heat waves	Storms	Heavy Precipt.	Flooding	Subsidence	Drought	Commentary on co-benefits	Commentary on negative impacts
Hail net	Roof	LOW	SIMPLE							• Protects fragile elements of the envelope from hail.	• Hail nets may conflict with the aesthetic design or cultural value of the building.
Avoid square and rectangular flat surfaces perpendicular to the wind	Building shape	LOW	SIMPLE							• Triangular-shaped buildings with edges to the wind will have a breaking effect on horizontal rainfall intensity.	• Flat surfaces perpendicular to the wind receive more intense wind-driven rain, especially at the top corners.
Green roof (extensive or intensive)	Roof & vegetation	LOW	SIMPLE							• Improved roof insulation reduces the energy need for heating and cooling. • Supports local biodiversity and water retention if appropriate plants are selected. • Research has shown that green roofs can be designed to withstand Category IV hurricane strength lateral winds without damaging or displacing any of the components.	• Additional materials required for structural elements; associated increase in embodied carbon. • An intensive green roof that can support biodiversity and has a relatively high-water retention capacity requires a flat roof. However, pitched roofs offer better protection than flat roofs against water penetration into the building.
Pitched roofs	Roof	LOW	SIMPLE							• A pitched roof has a higher stability than a flat roof.	• Not possible to install blue and blue-green on pitched roofs
Heat tracing in gutters	Roof	LOW	SIMPLE							• Heat tracing can prevent ice forming and the consequential blocking of gutters.	• Requires additional energy; conflicts with climate change mitigation aims.
Inspection and cleaning of the roof drain, gutters and downspouts, and snow	Roof	LOW	SIMPLE							• Reduces the risk of roof collapse by snow load in winter. • Reduces the risk of water infiltration	• No negative climate adaptation impacts have been noted
Infiltration trenches	Vegetation	LOW	SIMPLE							• Increased infiltration rate reduces risk from pluvial flooding	• Water infiltration close to foundations could increase vulnerability to subsidence
Anti-return valves for toilets and sinks	Services	LOW	SIMPLE							• Prevents property flooding from backflow through drainage and sewer systems during heavy rain. Requires regular maintenance and replacement.	• No negative climate adaptation impacts have been noted
Permeable or pervious soils	Vegetation & space considerations	LOW	SIMPLE							• Increase in biodiversity can be achieved if permeability is increased by vegetation, and the choice of vegetation is indigenous and appropriate for the local climate.	• Permeability close to foundations could increase vulnerability to subsidence. • Consider whether the soil is prone to shrinkage and swelling
Hail proof blinds and shutters	Windows	LOW	SIMPLE							• Provides protection against hailstones, but can also provide shelter from solar radiation and heat stress.	• May conflict with the aesthetic design or cultural value of the building.
Good sealing	Windows	LOW	MODERATE							• Careful design and sealing will prevent moisture and water from entering the building. • Improves the insulation of the building and reduces he likelihood of mould growth.	• No negative climate adaptation impacts have been noted
Disconnect surface water from sewage system	Services	LOW	MODERATE							• Reduces the risk of flooding from backflow or overflows of sewage system (and associated health risks). Requires connection to a rain barrel, water storage or area of permeable ground to allow infiltration into the soil.	• No negative climate adaptation impacts have been noted
Placement of sinks/toilets above the flood level	Services	LOW	MODERATE							• Reduces risk of inflow into the building in the event of flooding	• No negative climate adaptation impacts have been noted
Drainage network dimensioned to future runoff projections	Services	LOW	MODERATE							• Increased capacity of the network reduces the risk of overflow or flooding	• No negative climate adaptation impacts have been noted
Rain gardens and swales	Vegetation & space consideration	LOW	MODERATE							• Can be combined with rainwater harvesting measures. • Contributes to increased biodiversity.	• Must be placed at an appropriate distance from buildings; overflow may occur in heavy rainfall or flooding
Warm roof (waterproof layer overlaying an insulation layer)	Roof	MEDIUM	SIMPLE							• Increased insulation can reduce heating need.	• Adds height to roof and may impact roof drainage details.
Metal for roofing	Roof & preferred material	MEDIUM	SIMPLE							• Provides protection against hailstones and storm debris.	• Metal roofing may have a higher level of embodied carbon than other forms of roofing. • Metal roofing may conflict with aesthetic design or cultural value.

Building solutions, by priority hazard

Heavy precipitation

Solution	Category	Cost	Ease of Implementation	Heat waves	Storms	Heavy Precipt.	Flooding	Subsidence	Drought	Commentary on co-benefits	Commentary on negative impacts
Blue roofs	Roof	MEDIUM	MODERATE							• Depending on roof strength, this can provide additional capacity for water storage and mitigate pluvial and fluvial flooding. • Evaporation of water can cause a very short-term cooling effect.	• Without an additional roof covering, such as slabs on pedestals, it conflicts with other uses for flat roofs such as biodiversity or energy production. • Increases weight on roof and the amount of material required in structural elements; resulting in higher embodied carbon.
Blue-green roofs	Roof & vegetation	MEDIUM	MODERATE							• Blue-green roofs can provide water storage and mitigate pluvial and fluvial flooding. • Blue roof water storage can be used to water plants, reducing the stress on tap water usage in case of drought. • Green roofs can reduce temperatures to counter the effects of heat stress. • Using the appropriate choice of vegetation for the green roof can contribute to an increase in biodiversity.	• Blue roofs require a flat roof, so cannot be combined with solutions like pitched or domed roofs.
Sustainable urban drainage system (SuDS)	Services & vegetation	MEDIUM	COMPLEX							• Reduces risk of sewage overflow (and subsequent health risk). • Depending on the design, SuDS can also contribute to an increase in biodiversity. • Vegetation as part of a SuDS contributes to heat reduction.	• SuDS require regular maintenance, which can be costly.
Inverted roof	Roof	MEDIUM	MODERATE							• The insulation protects the membrane from extremes seasonal temperatures. • Lower maintenance costs than conventional roofs. • Suitable for roof terraces and flat roofs with heavy foot traffic.	• No negative climate adaptation impacts have been noted.
Ground preparation (mitigating landslides)	Structure	HIGH	COMPLEX							• Reduces the risk of foundations becoming displaced in precipitation induced landslides. • Improves groundwater drainage. • Enables passive control to deviate landslide/debris material/ avalanche away from buildings.	• Requires significant invasive works. May not be suitable for existing building plots.

Building solutions, by priority hazard

Flooding

Solution	Category	Cost	Ease of implementation	Heat waves	Storms	Heavy Precipt.	Flooding	Subsidence	Drought	Commentary on benefits	Commentary on negative impacts
Wet floodproofing (vents, internal drainage system, etc.)	Foundations	LOW	SIMPLE							• Lower economic costs than dry proofing a building	• An extensive clean-up is required after a flooding event; contamination can occur.
Square shape	Building shape	LOW	SIMPLE							• More resistant to horizontal loading of flood water	• Orientation may expose building to increased wind-driven rain and water ingress; flat surfaces perpendicular to the wind receive more intense wind-driven rain, especially at the top corners.
Temporary flood barriers (flood shields, sandbags, deployable and inflatable barriers)	Windows & doors	LOW	SIMPLE							• Low cost and unobtrusive.	• Temporary flood barriers can be successfully deployed when an early warning system is in place.
Electrical and mechanical systems and utilities above flood level	Services	LOW	SIMPLE							• No co-benefits were identified	• May reduce easy access to service systems.
Permanent flood barrier (automatic barriers, flood walls, retractable barriers)	Windows & doors	LOW	SIMPLE							• Depending on the material, flood barriers for windows could also be used to block heat and hailstones.	• Permanent flood barriers may conflict with the aesthetic design or cultural value of the building.
Water repellent finishes	Preferred materials	LOW	SIMPLE							• Coatings minimise the entry of moisture into the wall assembly and protect walls from deterioration in areas experiencing frequent wind-driven rain.	• Not appropriate for all building fabric types and heritage buildings. • May reduce breathability of the building fabric, reducing its energy performance and potentially promoting mould growth.
Water-resistant insulation (EPS and XPS)	Preferred materials	LOW	SIMPLE							• Can withstand contact with water. • Ensures thermal insulation	• Some materials can be flammable and contribute to spread of flames across a building.
Water-resistant materials	Preferred materials	LOW	SIMPLE							• Can withstand contact with water for at least 72 hours. • Preserves the interior spaces (from flood damage), particularly the lower floors.	• No negative impacts on other hazards have been noted.
Buffer zones around the building	Space considerations	LOW	SIMPLE							• Allows flood water to overflow. • Reduces the intensity of flooding.	• No negative impacts on other hazards have been noted.
Water resistant materials (plaster-based coating or water-repellent mortar)	Walls & preferred materials	MEDIUM	SIMPLE							• Several materials can be used. Examples are concrete, glass and ceramic.	• Most insulation material is not water resistant but is required to reduce building energy consumption. • Water resistant materials may conflict with aesthetic design or cultural value of building. • May reduce breathability of the building fabric, reducing its energy performance and potentially promoting mould growth.
Conduct a preliminary soil study and control the humidity level of the soil	Foundations	MEDIUM	MODERATE							• Protects foundations from settlement/displacement in the event of high precipitation.	• No negative impacts on other hazards have been noted.
Elevated structure	Foundations	HIGH	MODERATE							• Prevents flood damage to the building	• Design should take into account uplift and potential damage from strong winds. • Additional building materials; associated increase in embodied carbon.
Dry floodproofing	Primary structure	HIGH	MODERATE							• May be more effective for high-velocity flooding and wave action when compared to wet floodproofing	• Severe structural damage if structure fails.
Drainage system around the building	Space considerations	HIGH	MODERATE							• Reduces the amount of infiltration into the soil. • Increases the safety of the structure	• No negative impacts on other hazards have been noted.

Building solutions, by priority hazard

Subsidence

Solution	Category	Cost	Ease of mplementation	Heat waves	Storms	Heavy Precipt.	Flooding	Subsidence	Drought	Commentary on benefits	Commentary on negative impacts
Keep trees at a safe distance from the building	Vegetation	LOW	SIMPLE							• Reduces risk of drought-induced subsidence. Trees absorb water from soil which can lead to soil desiccation, shrinkage and subsidence. • Reduces risk of tree roots damaging building foundations. • Trees through their roots, and some through their leaves, promote higher infiltration rates which is a solution for heavy precipitation.	• Missed opportunities to provide shading to building.
Homogenous foundations (avoid partial basements)	Foundations	MEDIUM	SIMPLE							• Prevents differential movement; this is particularly important for buildings located on sloped terrain	• Additional material may be required and if concrete is used this causes a high impact from embodied carbon.
Impermeable peripheral pavement around the building	Space consideration	MEDIUM	SIMPLE							• Protects the building foundations from water infiltration and prevents shrinking-swelling of soils around the building. • Collection system can be installed to manage runoff water.	• Can increase surface water run-off into the surrounding area or drainage system if not appropriately managed.
Peripheral draining system around the building	Space consideration	MEDIUM	SIMPLE							• Limits the moisture variations near the foundations; contributes to avoiding the shrinking- swelling of soils.	• No negative impacts on other hazards have been noted.
Stronger, larger foundations	Foundations	MEDIUM	MODERATE							• Larger foundations provide a greater load carrying capacity offering a greater degree of redundancy against negative impacts.	• Additional material may be required and if concrete is used, this casuses a high eimpact from mbodied carbon..
Structural strengthening (horizontal, vertical, and diagonal reinforcements)	Wall	MEDIUM	MODERATE							• Provides stability throughout the building structure so it can resist soil movements.	• No negative impacts on other hazards have been noted.
Movement joints within a building	Wall	MEDIUM	MODERATE							• Differential movement may be experienced with the foundations and can be mitigated with movement joints. • Movement joints allow for thermal expansion and contraction.	• Movement joints can become complex and may affect the aesthetics of the building.
Movement joints between adjoined buildings	Wall	MEDIUM	MODERATE							• Beneficial for adjoining buildings with different foundations depths / solutions as it allows for independent movement between buildings.	• Movement joints can become complex and may affect the aesthetics of the building.
Underpinning	Foundations	HIGH	COMPLEX							• Provides additional support for the building and a greater load carrying capacity offering a greater degree of redundancy against negative impacts	• Additional material may be required and if concrete is used, this casuses a high eimpact from mbodied carbon.
Buoyant foundation in amphibious buildings	Foundations	HIGH	COMPLEX							• Ability to float enables building operations/activities to continue in the event of flooding.	• Additional materials required in foundations. Careful consideration of waterproofing materials is required

Building solutions, by priority hazard

Drought

Solution	Category	Cost	Ease of Implementation	Heat waves	Storms	Heavy Precipt.	Flooding	Subsidence	Drought	Commentary on co-benefits	Commentary on negative impacts
Water efficient fixtures and fittings	Services	LOW	SIMPLE							• Conserves water; reduces consumption and waste.	• No negative impacts on other hazards have been noted.
Designating water stressed areas	Space consideration	LOW	SIMPLE							• Contributes to identifying vulnerability of buildings to subsidence, particularly on subsidence-prone soils such as clays.	• No negative impacts on other hazards have been noted.
On-site water source such as on-site water storage or wells that can supply water for three to four days	Services	MEDIUM	SIMPLE							• Promotes the conservation of water. • Provides supply of water during periods of scarcity.	• No negative impacts on other hazards have been noted.
Nature based solutions	Vegetation	MEDIUM	MODERATE							• Promotes water retention in soil	• No negative impacts on other hazards have been noted.
Rainwater harvesting	Roof	MEDIUM	MODERATE							• Storage of water can help provide a continuous supply of water during periods scarcity.	• No negative impacts on other hazards have been noted.
Greywater recycling	Services	MEDIUM	MODERATE							• Water can be recycled and used for example for irrigation increasing the conservation of water. • Can provide additional water access during a period of water scarcity.	• Space and loading considerations for tank.
Air-handling unit (AHU) condensate capture and reuse	Services	MEDIUM	COMPLEX							• Promotes the conservation of water.	• Complex system to install. • Water may need further treatment for specific re-use cases.

Appendix B

Best practice considerations for industry actors

This section presents the various actions and considerations actors across the building industry can take to ensure building-scale climate adaptation. A summary of actions is provided for:

- government, regulators and local authorities;
- design teams (engineering and architecture);
- building users, facility managers and owners;
- investors, developers and insurance provides.

Governments, Regulators and Local Authorities

Overarching climate-adaptation measures	• Ensure good quality data is accessible to the public. Data on current and future climate trends, risks and vulnerability should be made available to ensure industry actors can make informed decisions and avoid the costs of delayed adaptation action. • Understand local climate risks and impacts. • Establish monitoring and early warning systems for key climate risks and hazard events. Ensure risks are communicated to the public via push messaging or broadcasts in a timely manner. • Incorporate resilience measures to build back better into local hazard adaptation plans. • Implement policies, regulations, standards and building codes that facilitate the inclusion of climate risk considerations. Circular economy principles, design for disassembly and lifecycle carbon assessments should also be supported in the built environment. • Ensure buildings meet safety requirements through inspections.
Heat waves	• Establish building codes and requirements for risk assessment documentation to be completed at building design and construction phases, to prevent overheating in buildings. • Develop campaigns to raise awareness of heat-related health and wellbeing risks. • Review opportunities to implement the following adaptation measures in neighbourhood, district or large-scale urban plans: - Green spaces and networks for airflow - Vegetation and trees for shading - Water bodies to cool air - District cooling systems For further detailed information, refer to Section 1 and Section 1.5.1.
Storms	• Develop policies to encourage the implementation of alternative energy sources to support critical facilities, such as hospitals, to ensure they can remain operational during storm events. • Review opportunities to install microgrids and bury distribution power lines to provide communities with a secondary energy source if central grids fail during storm events. For further detailed information, refer to Section 2 and Section 2.5.1.

Heavy Precipitation	• Engage with knowledge and awareness raising networks such as the C40 Cities Urban Flooding Network. • Incorporate adaptation measures into the permitting process for new buildings. This could include a condition on the installation of water retention systems or preventing the construction of new builds on areas prone to flooding. For further detailed information, refer to Section 3 and Section 3.5.1.
Flooding	• Establish online maps to assess the risk of flooding in local areas. This should incorporate data on changing sea-levels and precipitation to ensure a comprehensive overview of flooding risks. • Establish flood management plans, in accordance with the EU Flood Directive's international framework. • Limit building on flood plains through land use regulation and the permitting process. • Establish early warning systems for floods, along with government-led awareness campaigns. For further detailed information, refer to Section 4 and Section 4.5.1.
Subsidence	• Develop subsidence monitoring systems in areas with high clay content, areas prone to heavy precipitation or areas prone to drought. • Develop subsidence-related risk assessment requirements across the construction industry. For further detailed information, refer to Section 5 and Section 5.5.1.
Drought	• Ensure resources such as drought-risk maps and accurate weather forecasts supported by early warning systems are easily accessible by the public. • Identify and designate water stressed areas. • Encourage the installation of water recycling systems by raising awareness of drought risks and making funding available to support their implementation. • Refer to the European Commission's guidance on climate proofing infrastructure for droughts (European Commission, 2021). For further detailed information, refer to Section 6 and Section 6.5.1

Best practice considerations for industry actors

Investors, developers & insurance providers

Overarching climate-adaptation measures	• Identify the likelihood and impact of climate-related hazards using risk maps, vulnerability assessments and climate risk forecasts. • Incorporate uncertainty in climate forecasts (and associated hazards/risks) over the lifecycle of a (new) building. • Consider property or portfolio's exposure to immediate and future risks. • Seek to understand the extent to which adaptation is incorporated in potential investment portfolios and evaluate the cost of adaptation measures.
Heat waves	• Require a climate risk assessment process from design teams • Assess real estate assets contributions to heat wave adaptation (required under the EU Sustainable Finance Disclosure Regulation). Active adaptation planning will provide an advance on regulatory requirements in the coming years and will future-proof investments to a certain extent. • Consider need for thermal adaptation in renovations and new developments. • Consult the EU LEVEL(s) framework for assessing and reporting on building sustainability performance. This includes indicators on thermal comfort to ensure healthy and comfortable spaces. For further detailed information, refer to Section 1 and Section 1.5.2.
Storms	For Investors and insurance providers: • Develop an understanding of climate history and forecasts to assess storm risk and vulnerability of assets. For developers: • Consider wind pressure and wind tunnel effects when evaluating a site or potential developments. • Conduct additional risk assessments and modelling for tall buildings • Ensure the public realm and landscaping design and drainage is adapted to storm conditions. For further detailed information, refer to Section 2 and Section 2.5.2.
Heavy precipitation	Consider the need for drainage adaptation in renovations and new developments. For investors and insurance providers: • Develop a knowledge of risks associated with heavy precipitation in the local area/region. Assess previous damage claims and the type, amount and duration of heavy precipitation associated with them to achieve this. • European insurers are expected to integrate climate-related risks, including extreme rainfall and hailstorms, into their own risk and solvency assessments (ORSA), as expressed by the European Insurance and Occupational Pensions Authority (EIOPA). For further detailed information, refer to Section 3 and Section 3.5.2.
Flooding	Consult flood risk maps and flood risk zoning/regulation for the local area. For insurance providers: • Ensure flood risks, vulnerability and insurance options are clearly communicated to building owners and occupants. For further detailed information, refer to Section 4 and Section 4.5.2.

Subsidence	• Develop an understanding of meteorological and geological indicators that make buildings vulnerable to subsidence. • Review risk maps and soil composition maps to understand the location of soils prone to clay shrinking / swelling. • Identify whether early investment in subsidence adaptation or remedial interventions are required. This may require consultation with geotechnical engineering professionals. • Explore options to develop insurance coverage for subsidence. For further detailed information, refer to Section 5 and Section 5.5.2.
Drought	• Depending on the level of drought-risk, developers may need to install water-efficiency and storage solutions, as well as measures to protect against subsidence risk. For further detailed information, refer to Section 6 and Section 6.5.2.

Best practice considerations for industry actors

Design teams (engineering and architecture)

Overarching climate-adaptation measures	• Develop a strong understanding of the local environmental context and building codes. • Analyse current and future climatic conditions across all seasons using climate forecasting tools. This helps identify the extent and type of adaptation needed. • Conduct a climate vulnerability and risk assessment to determine relevant climate hazards and inform adaptation measures to be implemented. (See the climate vulnerability and risk assessment methodology study for further details). • Incorporate climate adaptation principles into the early design stage. • Explore the option to implement 'design for disassembly' at the design stage. • Conduct a series of stress tests on designs to identify robust solutions that adapt buildings to multiple hazards. • Reduce embodied carbon emissions over the full lifecycle of the building. Limit carbon intensive materials (e.g. steel and concrete) and high carbon design decisions (e.g. unnecessary long spans). • Use renovation as an opportunity to incorporate resilience and adaptation measures.
Heat waves	• Understand projected climatic conditions including temperature peaks, hours of sunshine, heating, and temperature variability. • Carefully assess the building orientation and shape as this can help to reduce exposure of the building by considering the path of the sun. • Use dynamic thermal analysis to assess thermal and energy performance of the building, under current and future climates, and predict the risk to overheating. • Design passive and natural ventilation systems, using modelling thermodynamic simulation tools. • Orientate and design interior spaces to enable effective ventilation and passive cooling of air. • Consider the interactions between measures to insulate and ventilate the building. Solutions should moderate building temperatures through both summer and winter months, whilst reducing the need for active cooling and heating. For further detailed information, refer to Section 1 and Section 1.5.3.
Storms	• The location and orientation of the building may affect the direction and level of protection against wind forces – avoid low lying areas prone to flooding and areas exposed to high winds. • Incorporate wind engineering considerations and testing in the design. • Gather information after critical storm events to develop localised understanding of how building performance could be enhanced. • Continuously check and implement the latest building codes and preferred materials. Materials should perform well under wind-pressure and heavy precipitation. • Design with the lowest liveable floor elevated above ground level, with appropriately anchored foundations. • Incorporate roof draining systems and a robust rainscreen design or cladding into the building design. Sub-roofing and sheathing should be considered to reinforce the roof against high winds. For further detailed information, refer to Section 2 and Section 2.5.3.

Heavy precipitation	• Conduct research on the amount and type of heavy precipitation specific to the region. Consider that estimates based on historical data may underestimate the frequency and intensity of heavy precipitation. This should influence the type of adaptation solutions being considered. • Use hydrometric analysis to identify flow rates of water on the building and incorporate this in the design of the drainage scheme on the plot. • Consider the level of the building compared to its surroundings to prevent runoff from entering the building, during construction and after. • Roof strength should be designed so that blue-green roofs can be installed. • Ensure appropriate choice in vegetation in the design of blue-green roofs. • Consider building materials that are water and hail-resistant. For further detailed information, refer to Section 3 and Section 3.5.3.
Flooding	• Assess the plot (and the wider area's) vulnerability to flood risk and undertake topographic analysis. • Building on locations with high flood risk (due to sea-level rise, river flooding or heavy precipitation) should be avoided. • Where avoidance is not possible designs should consider adequate foundations, elevated entrances to buildings, and consider wet or dry floodproofing in the design. • Consider adaptations to the primary structure to strengthen the building against strong water flow. • Consider flood-resistant materials that can withstand contact with water for at least 72 hours (i.e. stone, polythene floor membranes, or concrete-based water-resistant floor finishes). • Consider designing the ground floor as a buffer zone or 'sacrificial basement' • Elevate essential equipment and user activities to upper floors to ensure building operations can continue in flood events. • Refer to BREEAM's International New Construction Manual's assessment of flood risk and building adaptation. For further detailed information, refer to Section 4 and Section 4.5.3.
Subsidence	• Carry out a risk assessment and soil surveys to determine the grounds structural stability. This would include assessing the composition of soils and exposure to subsidence. • Use exposure maps and weather pattern predictions to help develop scenarios and to evaluate how climate change may impacts the soil over the lifecycle of the building. • Conduct geotechnical surveys to assess stability of soil during construction to prevent damage from occurring during this phase. • Effective soil quality management during the site preparation stage is important to avoid the risk of soil erosion and reduce the risk of subsidence further down the line. • Incorporate movement joints in the building design and ensure any adjoining buildings have the same depth foundations. For further detailed information, refer to Section 5 and Section 5.5.3.
Drought	• Ensure efficient water re-use and water collection systems are part of the building design. • Ensure water collection and re-use storage tanks are located on solid foundations, away from direct sunlight. • Install water-saving fixtures to reduce household water consumption andincrease conservation and reuse. For further detailed information, refer to Section 6 and Section 6.5.3

Best practice considerations for industry actors

Building users, facility managers and owners

Overarching climate-adaptation measures	• Informing building users of the climate risks the building can be exposed to. Informed and trained building users and occupants can help establish building protection measures and emergency evacuation plans to reach safety in an organised manner if needed. • Raise awareness amongst building users and managers to reduce the physical risk from climatic hazards. This can be through signage or booklets inside the building or via training. • Conduct regular maintenance, checks and repairs of buildings structures and systems. This should aim to identify any faulty systems or failures in the building fabric. • Implement automated building monitoring and management systems, such as smart thermostats and sensors. • Use renovation as an opportunity to incorporate resilience and adaptation measures.
Heat waves	• Assess thermal comfort using smart / automated devices. This can help optimise shading, ventilation and active cooling strategies. • Regularly conduct checks, cleaning and repairing of ventilation systems to ensure they do not become blocked. • Ensure automated ventilation or shading elements are set to optimal performance. • Install window blinds or mechanical ventilation (as appropriate). • Ensure building users are capable of operating cooling systems through training and information. For example, share knowledge on the best times to open windows, identify spaces which are coolest during peak temperatures, how to maintain cooling in indoor spaces, and how to ensure an energy-efficient operation of day-to-day equipment to minimise internal heat sources. • Monitor and reduce heat generated by IT equipment. • Maintain any healthy vegetation that can provide shade to the building. **When renovating buildings:** • Assess opportunities to reorganise the layout of interior spaces to optimize solar gain all year round. • Upgrade windows and walls with improved insulation. • Consider replacing glazing with low solar gain, vacuum or smart glass alternatives. Fritting can be applied to existing glazing. • Assess the potential to reinstate passive cooling measures (before mechanical systems are installed). • Ensure sash and case windows are maintained and operable. • If appropriate in traditional buildings, install shutters set into window reveals to control sunlight. Rollerblinds can be a low-level alternative intervention. For further detailed information, refer to Section 1 and Section 1.5.4.

Storms	• Managers and owners can implement many technical solutions listed in Section 2.3 to assess and improve a building's protection from high winds. • In addition to these, building owners and facility managers should regularly check properties to : - replace missing slates or tiles on the roof; - regularly check that gutters and pipes are clear from blockages and are fixed securely; - ensure dead trees are pruned or removed accordingly, and check for disease; - ensure the surrounding vegetation does not potentially cause damage in high winds. **When renovating buildings:** • Impact-resistant glass should be used on windows and can either be introduced during the manufacturing process, or added to existing windows with a film. • When retrofitting a roof, reinforced of sheathing from the attic floor to the wall and roof should be considered. For further detailed information, refer to Section 2 and Section 2.5.4.
Heavy precipitation	Building owners and facility managers can apply a range of building measures to prevent damage from heavy precipitation. These measures support either: • an increased water infiltration rate: measures include removing tiles around the building and replacing them with plants; the installation of green facades or the installation of anti-return valves in sanitary pipes; or • a reduced risk of sewerage overflow: measures include disconnecting rainwater drainage from the sewage network and instead connecting it to a rain barrel, water storage or a soak away into the ground. Regular checks and maintenance of green roofs, blue-green roofs, green facades, drainage and downspouts should be conducted to prevent blockages (and risk of damage or collapse from snow load in cold winters). **When renovating buildings:** • Consider opportunities to install water repellent or water-resistant materials or treatments. Ensure this does not negatively impact the breathability of the building fabric; • Prevent decay in timber windows resulting from water infiltration by painting, regular maintenance and repairs; • Re-secure loose joints in traditional timber buildings by cramping, gluing, re-wedging and pinning. Decayed joints should be taken apart and the defective parts repaired by piecing-in. New wood and as much of the existing wood should be treated with a solvent-borne preservative before fitting. For further detailed information, refer to Section 3 and Section 3.5.4.

Building users, facility managers and owners

Flooding	• Ensure electrical and building operation installations are elevated or raised out of areas that could be prone to flooding. • Establish emergency response plans. This could involve setting up a refuge zone to ensure the safety of buildings or emergency evacuation plans. Emergency supplies and bedrooms should be located above flood level. • Regular checks and the maintenance of gutters and pipes should ensure they are always clear and fixed securely. • Installation of temporary or permanent flood barriers can prevent damage in the case of (short duration) floods. • After a flooding event check that the adaptation solutions adopted are in good condition and continue to perform as expected. There will be a need to dry, clean and repair flood-affected buildings. **When renovating buildings:** • Consider installing water repellent or water-resistant materials or treatments to walls and insulation. • Dry or wet floodproofing may be implemented as part of a retrofit. • In traditional buildings, where flood-repellent materials or features may conflict with cultural heritage value, consider installing temporary flood barrier to entrances and openings. For further detailed information, refer to Section 4 and Section 4.5.4.
Subsidence	• Inspect buildings regularly throuhout their lifecycle for signs of subsidence. Notable signs include the appearance of cracks in a building's internal or external envelope. This is particularly important during and after a period of prolonged dry weather, or drought. • Regularly check the buildings plumbing, drainage, and stormwater systems to explore whether they have been affected by instances of subsidence. **When renovating buildings:** • If new services or alterations to the primary structure takes place during renovation, consideration should be paid to the effects this has on the foundations and stability of the building. For further detailed information, refer to Section 5 and Section 5.5.4.
Drought	• Install rainwater- harvesting solutions. • Install water-saving fixtures; also increase conservation and reuse to reduce household water consumption. All these measures are important for ensuring building users are prepared for periods of water scarcity. • Perform regular checks for leakages and pipe breaks to avoid water loss. • As droughts can lead to drought-induced subsidence, considerations described under subsidence may apply. **When renovating buildings:** • Assess the possibility of upgrading water systems so that water efficient systems and water-saving fixtures and fittings are part of retrofitting and renovating For further detailed information, refer to Section 6 and Section 6.5.4.

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