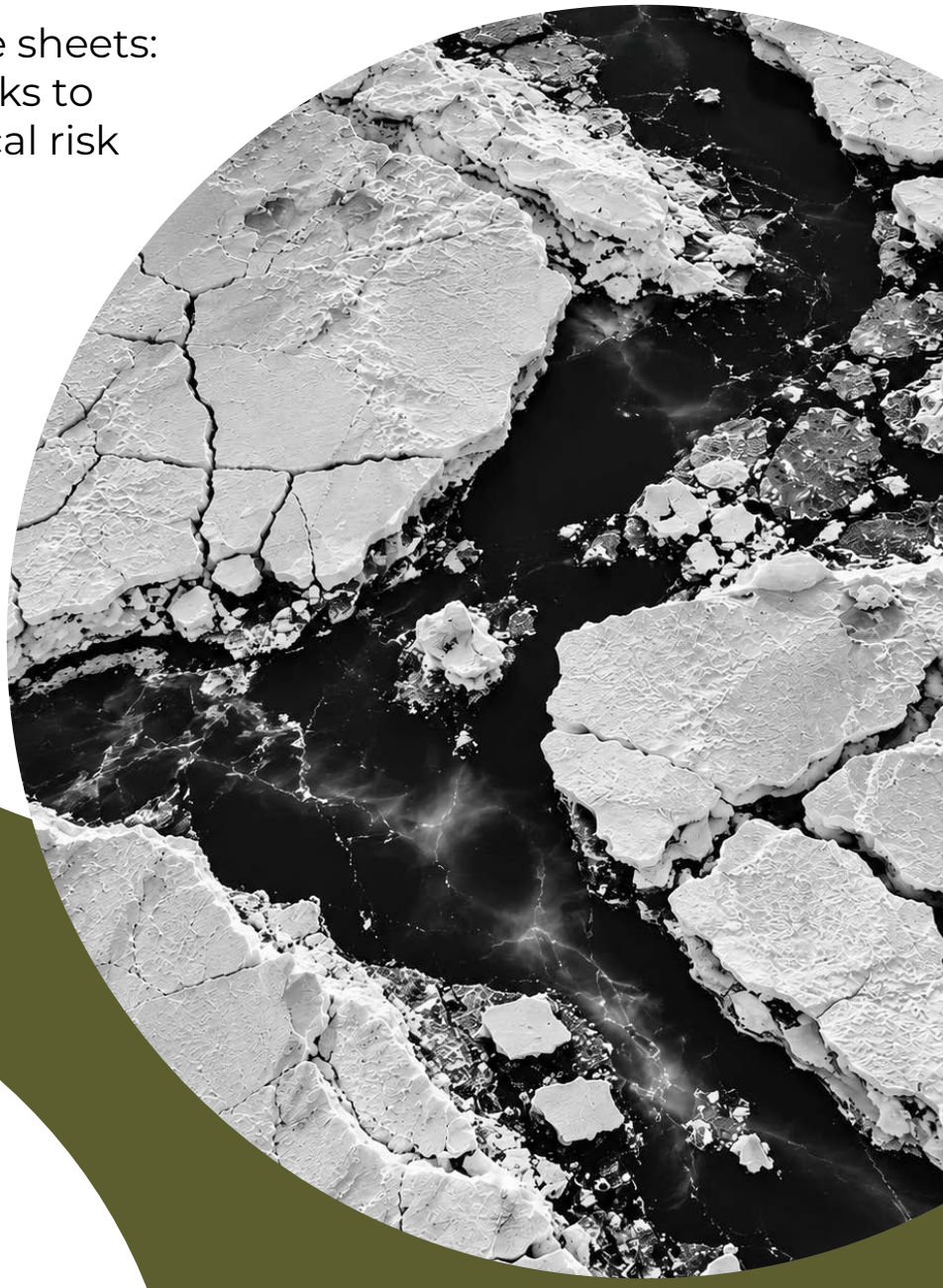
C-ESG RISK ROUNDTABLE

Physical Risk Workstream

Report N° II

From hazards to balance sheets:
a practical guide for banks to
assess and model physical risk



November
2026

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ABOUT THE C-ESG RISK ROUNDTABLE

To further strengthen the dialogue between banking sector and supervisors as well as facilitate incorporation of risk elements related to climate and environment into banks' risk management, a high level Environmental, Social, and Governance Risk Roundtable (C-ESG Risk RT) was set up in late 2022 by the European Banking Federation under the existing CEO Roundtable (CEO RT), with the participation of 14 European banks, and the EBF and the ECB as observers.

The C-ESG Risk RT focuses on climate risks with the objective to discuss current practices, identify gaps and promote pragmatic and practical approaches that are being shared with the entire banking industry to support and facilitate their implementation efforts and enhance harmonisation where relevant and possible.

The results of the workstreams' (WS) deliberations are presented publicly via a series of EBF webinars and are made available on the EBF website in the form of thematic papers. The views in these papers reflect the discussions of the WS members (contributors) and any suggestions in these publications are of a voluntary nature. The sole purpose of the initiative is to identify existing gaps and approaches and share such experience and knowledge to increase the level of collective awareness and deepen future dialogues on these topics that are expected to further evolve over time. Individual institutions are free to consider the relevance of a particular approach for potential implementation within their own organisation.

EXECUTIVE SUMMARY

Physical risk is becoming an increasingly important financial risk for banks. Physical hazards are already causing asset damage, business interruption and wider economic losses, while climate change is altering the frequency and severity of many hazards. Banks are exposed through their clients, collateral and financial assets, and insurance cannot always be assumed to absorb the resulting losses. At the same time, adaptation and resilience create substantial financing needs. Understanding physical risk is therefore increasingly important both for managing risk and for supporting clients in building resilience.

Banks increasingly have access to detailed information on physical hazards, from flood depths and heat stress to drought, wildfire and water stress. Turning that information into decision-useful financial risk remains much harder. **How does a physical hazard affect a company, property or portfolio, and through what mechanism does that impact become a risk for the bank?**

This report develops a practical framework for answering those questions. It establishes a common language for physical risk assessment, unpacks the transmission mechanisms from hazard to banking outcome, and brings together modelling practices and resources for quantifying the different parts of that chain.

Establishing a common language

Physical-risk modelling brings together climate science, catastrophe modelling, engineering, economics and banking risk, often using similar terminology in different ways. The report establishes a common language for **physical hazards, banking products and underlying entity types, banking use cases and banking transmission channels.**

A key distinction is between **physical transmission pathways,** which describe how hazards affect entities and assets and generate operational and financial consequences, and **banking transmission channels,** which describe how those consequences enter the bank's risk position.

This provides a common architecture for physical risk assessment. The entity or asset, its relevant locations and dependencies, the hazards to which it is exposed, and the banking outcome of interest establish **what needs to be assessed.** The intended use, whether an individual lending decision, portfolio analysis or stress test, determines the level of specificity, coverage, aggregation and time horizon required.

Unpacking how physical risk becomes banking risk

Physical risk matters to a bank when a physical hazard, such as a flood, drought or heatwave, affects a corporate or asset in a way that ultimately creates financial risk for the bank. This report follows that chain from the hazard, through its impact on the client or asset, to the resulting financial consequences and ultimately the risk for the bank.

For corporates, the impact can arise in several ways. A hazard may damage a factory or other asset, but physical damage is only part of the picture. A company may also be unable to operate because a critical supplier is disrupted, water or electricity is unavailable, transport infrastructure fails, or employees

cannot work. Physical risks can also cause changes in demand, prices and competitive conditions, while wider impacts on growth, inflation and financing conditions can affect counterparties through the broader economy.

For real estate, physical hazards can lead to repair or adaptation costs, make a property less suitable or attractive to use, reduce rental income or lower its value. They may also weaken the financial position of the borrower.

Together these pathways ultimately show up in familiar financial measures: **lower revenues, higher costs, weaker cash flows, lower asset values and reduced financial strength.** For a bank, this can translate into **a higher risk that a client cannot repay a loan, a reduction in the value of collateral, or a loss in the value of assets held by the bank.**

The proposed assessment structure in this report takes physical risk assessment **beyond asset damage and aims to include all relevant transmission pathways.** Damage to buildings and equipment remains important, but it represents only one route through which physical hazards can affect financial outcomes. A company with an undamaged factory may still be unable to produce because a critical supplier, transport corridor, electricity network, labour pool or water resource has been disrupted.

This distinction also matters for **how the risk is assessed.** Where a hazard directly affects an identifiable location, the assessment considers **what hazard the location is exposed to, what assets or activities are there, how vulnerable they are, and what damage or disruption could result.** Where the impact arises elsewhere, for example through suppliers, infrastructure, markets or the wider economy, the assessment instead needs to understand **how that external disruption reaches the client and affects its financial performance**

Making these mechanisms explicit also makes the assessment more actionable. It helps banks understand what is driving the risk, how significant the financial impact could be, and whether adaptation, resilience measures or financial protection can reduce it.

Building a practical modelling toolkit

The report combines the transmission framework with detailed modelling guidance.

For site-level impacts, it brings together **hazard indicators, vulnerability approaches, modelling techniques, public-domain datasets, tools and literature** across temperature-, wind-, water- and solid-mass-related hazards. It also provides guidance on translating physical impacts such as asset damage, downtime and productivity loss into quantities that can feed into financial assessment.

The modelling guidance extends across **off-site operational, market and macroeconomic transmission.** It considers approaches for critical suppliers and other inputs, infrastructure and systems, labour availability, changes in demand and prices, and wider economic effects. Several pathways may be material at the same time, so the report also considers how their outputs can be brought together through common operational and financial drivers while recognising interactions and avoiding double counting.

Data gaps are unavoidable in physical risk assessment. The report therefore provides a clearer framework for the use of **proxies and approximations.** Site-level proxies may address missing hazard, exposure or vulnerability information, while wider transmission analysis may require approximations for suppliers, infrastructure dependencies, market relationships or macroeconomic effects.

The aim is to make clear **what has been approximated, why the proxy is appropriate for the intended use, and what the resulting estimate can support.** This is particularly important when balancing the need for detailed counterparty or asset insight with the broader coverage required for portfolio-level assessment.

Connecting modelling to banking risk management

The report then connects modelling outputs to measures used in banking risk management.

Physical and operational impacts can be translated into counterparty- and asset-level financial outcomes and subsequently into measures relevant to collateral value, client financial strength, credit risk and other banking applications. The report also considers inherent and residual risk and the different roles of adaptation, operational resilience, insurance and other financial risk-transfer mechanisms.

The practical value of physical-risk modelling ultimately lies in understanding **which mechanism is driving the risk, how material the resulting financial effect may be, and what could change that outcome.**

Building the foundation for further work

The framework and modelling practices developed in this report provide a foundation for further work on areas important to banks' practical management of physical risk. Potential areas for further work include:

- integrating **climate- and nature-related physical risks** within a common framework
- developing more actionable approaches to **supply-chain risk**
- improving shared resources and practices for **asset and insurance data**
- extending modelling good practices as methods develop, including **event-based approaches**
- developing good practices for **historical loss tagging,** and
- providing more detailed guidance on integration into **risk appetite, loan origination, provisioning and other risk-management processes.**

These are natural extensions of the work developed here: a clearer understanding of how physical risk arises provides the basis for improving how it is modelled, measured and managed.

1. INTRODUCTION

This is the second report of the C-ESG Risk Roundtable Physical Risk Workstream, building on the workstream's first report published in September 2024.

This report focuses on **how physical hazards translate into financial and banking risk and how the different parts of that transmission can be modelled.** It develops a common terminology and transmission framework and brings together practical modelling approaches, resources and examples across site-level impacts, wider operational dependencies, market effects and macro-economic transmission.

1.1. Why physical risk matters for banks

Physical risks are becoming an increasingly important consideration for financial institutions. The last eleven years were the eleven warmest years ever recorded globally, and 2025 was ranked among the three warmest years on record despite the cooling influence of La Niña [1]. Natural disasters caused an estimated US$224 billion in economic losses and US$108 billion in insured losses during 2025 alone [2].

Physical hazards can affect households, corporates, real estate assets, governments and financial institutions through asset damage and operational disruption, as well as through supply chains, labour markets, infrastructure systems and broader macro-economic conditions. These impacts can subsequently influence asset values, borrower affordability, financial strength, profitability, cash flow and creditworthiness, and transmit into multiple banking risk categories.

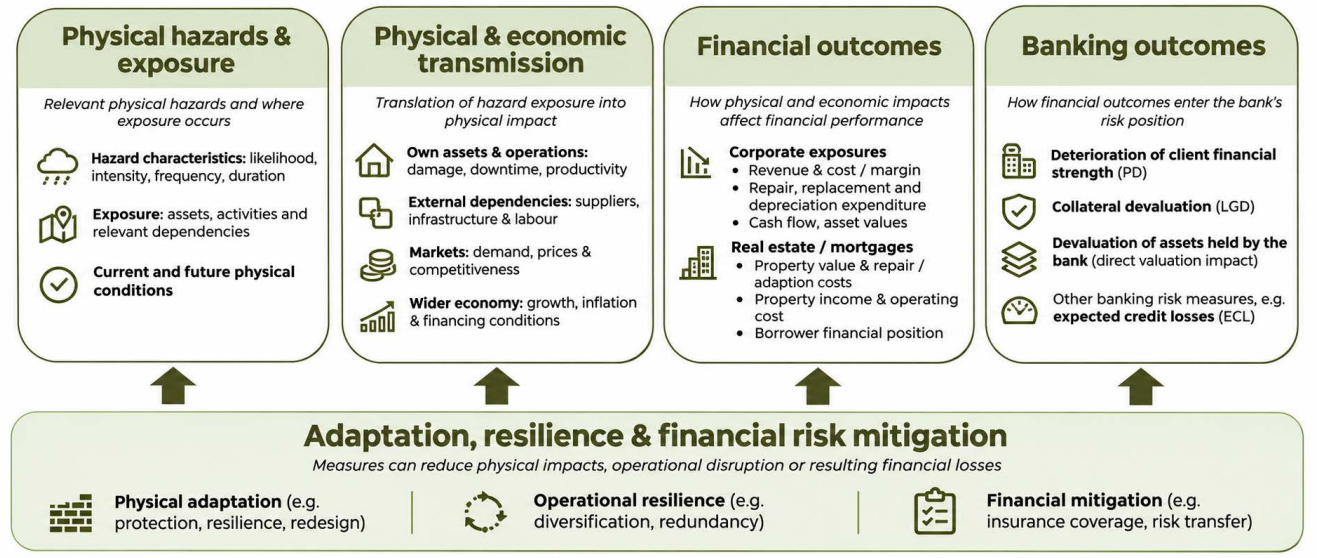
Physical risks are also closely linked to financing needs. Adaptation and resilience measures frequently require investment in protection, as well as infrastructure redesign and upgrade. Understanding physical risk is therefore important not only for risk management, but also for supporting the financing of adaptation and resilience.

1.2. From physical hazards to banking outcomes

The objective of a physical risk assessment is to translate hazard exposure into impacts on assets and operations, economic and counterparty financial impacts and finally banking outcomes.

Figure 1: From physical hazard exposure to financial and banking outcomes

How physical hazards translate into financial outcomes and banking risk



Physical hazards may damage assets, impair operations, disrupt inputs, reduce labour productivity or trigger wider economic disruption. These physical impacts can then affect the ability of borrowers to repay loans. For banks, these effects may translate into changes in expected losses and capital requirements, while their distribution across sectors, geographies and portfolios informs the assessment of physical risk concentrations.

Understanding this transmission chain is important because physical risk assessments support different banking decisions and risk-management activities. These range from individual lending, origination and collateral decisions to portfolio monitoring and risk appetite, scenario analysis and stress testing, and the incorporation of physical risk into credit risk assessment. Each application places different demands on the scope, granularity, time horizon and outputs of the assessment. The principal banking use cases considered in this paper are defined in Section 2.3.

Physical risk assessment therefore extends beyond the identification of hazards themselves. It requires understanding how hazards affect assets, operations and economic activity, as well as how those impacts translate into financial outcomes, and how those financial outcomes affect the bank.

1.3. Purpose of this paper

Despite substantial progress in recent years, physical risk assessment remains an evolving area of practice. Taxonomies, modelling approaches and data sources continue to develop, while terminology is often applied inconsistently across the industry. Institutions frequently use different concepts and frameworks to describe hazards, transmission channels, vulnerability, financial impacts and modelling methodologies. Physical risk data providers use a wide range of methodologies[1], and banks' disclosures of physical risks under Pillar 3 suggest there are disparate approaches.

At the same time, physical risk assessments face several practical challenges. Asset-level information is often incomplete, particularly for corporate portfolios where key information may be unavailable or difficult to obtain. Physical hazards may affect counterparties through multiple pathways simultaneously, including impacts on assets and operations, off-site impacts through supply chains and infrastructure systems, and market and broader macro-economic effects. Consistently assessing these transmission pathways remains an area of active methodological development.

This paper aims to contribute to a common language for physical risk assessment and to document good practices developed through the C-ESG Risk Roundtable. It brings together guidance on hazard identification, transmission pathways and modelling approaches to support more consistent and transparent physical risk assessments across banking use cases.

The choice of the term *good practice* is deliberate. Given the pace of development in physical risk data, scientific understanding and modelling methodologies, it would not be appropriate to present a definitive or final approach. Instead, this paper aims to provide a practical foundation that institutions can apply and further develop as physical risk assessment continues to mature.

1.4. Relationship to wider work

This paper builds upon existing work undertaken by various institutions, including the European Banking Authority (EBA), the European Central Bank (ECB), the Network for Greening the Financial System (NGFS), the Intergovernmental Panel on Climate Change (IPCC), and a growing body of industry methodologies and physical risk frameworks.

It should be viewed as a practical contribution to the ongoing development of physical risk assessment rather than a replacement for existing initiatives. The intention is to support consistent implementation by establishing common terminology, linking hazards to financial outcomes through transparent transmission pathways, and providing practical guidance on the application of different modelling approaches.

[1] See for example the 2025 GARP benchmarking study of physical risk data vendors A Risk Professional's Guide to Physical Risk Assessments

1.5. Interpreting physical risk assessments

Physical risk assessment remains subject to substantial uncertainty. Uncertainty arises from multiple sources, including future climate and environmental developments, hazard occurrence and severity, exposure data, vulnerability assumptions, adaptation responses and the modelling approaches used to quantify impacts.

Different assessments may focus on current conditions, future baseline developments, severe-but-plausible scenarios or extreme events, depending on the intended use case. In addition, future hazard projections are themselves conditional on assumptions regarding future climate pathways, socio-economic developments and model structure.

As a result, physical risk assessments should be interpreted as decision-support tools rather than precise forecasts. Model outputs are best understood as conditional estimates that help inform risk management, prioritisation and strategic decision-making under uncertainty. A key objective of good practice is therefore not to eliminate uncertainty, but to make assumptions transparent and ensure that uncertainty is appropriately understood and communicated.

1.6. Structure of the paper

The paper starts by establishing the **common language and conceptual foundations** for physical risk assessment. Chapters 2 and 3 define the key taxonomies and set out how physical hazards transmit through corporates, real estate, governments and financial institutions to financial outcomes and banking risk.

Building on these foundations, Chapters 4 and 5 turn to **modelling good practices**. They consider approaches for assessing site-level hazard impacts as well as off-site operational, market and macro-economic transmission, with a focus on selecting approaches that are appropriate to the transmission pathway and intended use.

Chapter 6 then provides a brief overview of **measures for risk management**, considering how physical, operational and financial impacts can be translated into measures that support banking risk management. Finally, Chapter 7 identifies areas for **further practical guidance and methodological development** through future work of the C-ESG Risk Roundtable.

2. TAXONOMIES

The definition of certain taxonomies is a prerequisite to defining good modelling practices. They provide a **common language,** establishing shared terminology for describing physical risk assessments and modelling approaches, while reflecting the diversity of products and risk assessment approaches used within financial institutions. Different exposures and assessment purposes may require different modelling approaches.

In developing a physical risk assessment, four questions need to be considered:

- Which **hazards** are potentially material?
- What are the key banking business line **products** and exposures that require a physical risk assessment?
- What are the main transmission **mechanisms** through which physical impacts can affect counterparties, assets and ultimately result in financial loss for banks?
- What are the main banking **use cases** for physical risk assessment?

These dimensions are related but play different roles in determining the appropriate assessment and modelling approach. The relevant transmission mechanisms are fundamentally driven by the exposure and underlying entity or asset being assessed: physical hazards affect, for example, residential real estate, corporates, government entities and financial institutions through different mechanisms. The use case, in turn, determines how those mechanisms need to be assessed, influencing the required granularity, time horizon, level of aggregation and output. The same underlying physical risk may need to be assessed differently for an individual lending decision, portfolio monitoring or a regulatory stress test.

For example, fluvial flood (also referred to as riverine inundation) is a physical hazard, while residential real estate lending is a banking product. For this product, one relevant transmission mechanism arises where an exposed and vulnerable property securing a loan suffers damage and then devaluation, potentially increasing the loan-to-value ratio and loss given default. The modelling required to assess this mechanism will depend on the intended use. An institution may assess the risk to an individual exposure at loan origination, aggregate such risks for portfolio monitoring, or assess future impacts under a stress-test scenario.

The four taxonomies defined in this chapter provide complementary dimensions of physical risk assessment rather than alternative classifications of the same thing. Their purpose is to provide a common terminology and help link the banking need and underlying exposure to the relevant transmission mechanisms and, ultimately, the modelling approach. Chapter 3 brings these dimensions together by describing the physical transmission pathways through which hazards affect different entity types and explaining how the relevant pathways and intended use inform the selection of modelling approaches.

2.1. Hazard taxonomy

Following the definitions of IPCC [3], a **hazard** refers to the potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources. [4] notes that for climate risk assessment, this could be a flood or storm, whereas for nature-related risks it could manifest as degradation of water quality or disease.

For the purposes of this paper, the starting point for identifying climate-related physical hazards is the **classification of climate-related hazards set out in the EU Taxonomy Regulation** CDR (EU) 2021/2139 [5]. This constitutes "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". Although explicitly non-exhaustive, the classification provides broad coverage of climate-related physical hazards and is widely used, making it a useful common reference point for the modelling practices discussed in this paper. The hazard categories from this classification are set out in Table 1; as discussed below, the acute/chronic distinction is not retained for the purposes of this paper.

Table 1: Climate-related hazards adapted from the EU Taxonomy classification of climate-related hazards [5]

	HAZARD NAME
Temperature-related	Changing temperature
	Heat stress
	Temperature variability
	Permafrost thawing
	Heat wave
	Cold wave/frost
	Wildfire
Wind-related	Changing wind patterns
	Tropical cyclone (cyclone/hurricane/typhoon)
	Storm
	Tornado

	HAZARD NAME
Water-related	Changing precipitation patterns
	Ocean acidification
	Saline intrusion
	Sea level rise
	Water stress
	Drought
	Heavy precipitation
	Flood (coastal, fluvial, pluvial, ground water)
	Glacial lake outburst
Solid Mass-related	Coastal erosion
	Soil degradation
	Soil erosion and solifluction
	Avalanche
	Landslide
	Subsidence

The EU Taxonomy also separates hazards into acute and chronic categories. This is useful for illustrative purposes, as it helps to characterise different manifestations of physical hazards and in the majority of cases is relatively unambiguous. For a small number of hazards, however, this distinction is better treated as a guide rather than a rigid restriction. Drought, for example, is classified as acute, although it may be represented either as an event of a given intensity and duration or through measures capturing persistent or recurrent dry conditions. Similarly, the IPCC distinguishes between slow-onset and sudden-onset events, both of which remain events: sea-level rise, for example, is a slow-onset process that can contribute to sudden coastal flooding.

For modelling purposes, it is therefore more useful to specify how a hazard is represented through relevant **hazard indicators** than to constrain modelling according to a strict acute/chronic classification. Depending on the relevant impact pathway, drought might, for example, be represented through the number of months per year in which the SPEI index falls below a specified threshold, annual dry-spell days, or the probability of occurrence or return period of a drought event of a given intensity and duration. The modelling good practices discussed in Chapter 4 therefore focus on the appropriate representation of individual hazards and do not prescribe different modelling approaches solely on the basis of the acute/chronic classification.

The EU Taxonomy classification identifies and names the relevant hazard categories but does not provide detailed definitions of the individual hazards. Such definitions are an important prerequisite for modelling, particularly where hazard categories are related or potentially overlapping, as they establish what physical phenomenon is being assessed before appropriate indicators can be selected to measure it. For the purposes of this paper, the EU Taxonomy hazard categories are retained as the common reference point; **Section 4.2** subsequently considers the indicators through which these hazards can be represented quantitatively for modelling purposes

A further question is how the climate-related hazard taxonomy should evolve as physical risk assessment expands to consider nature-related physical risk drivers. The EU Taxonomy classification provides the common starting point for the climate-related hazards considered in this paper. Developing an integrated approach that considers the full range of relevant physical risk drivers is beyond the scope of this paper and represents an important area for further work.

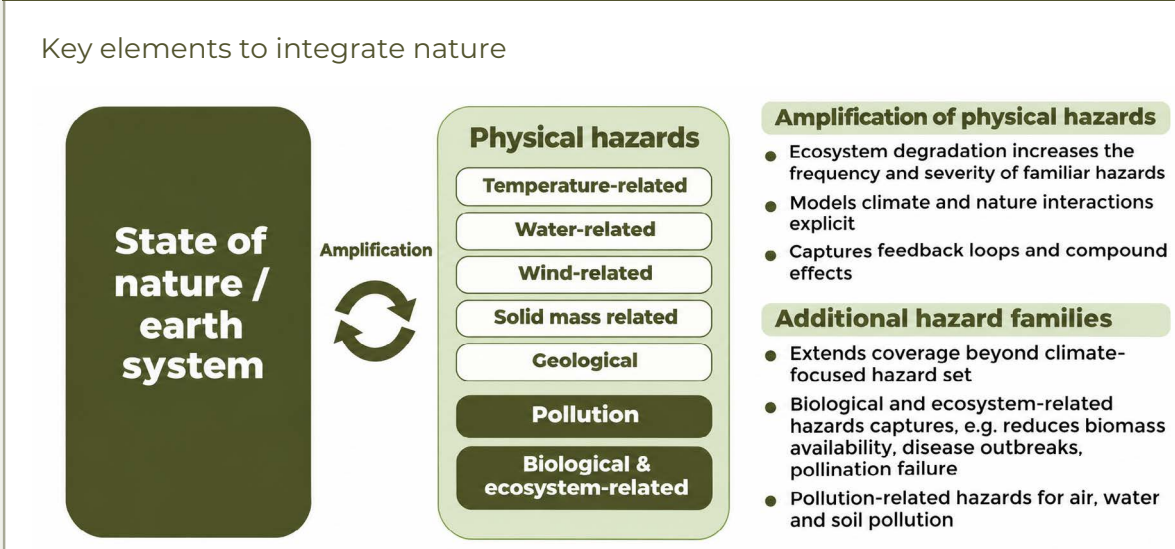
As a first step in this direction, the outlook below considers how nature-related degradation may interact with the existing climate hazard taxonomy, both by amplifying existing hazards and through additional nature-related hazards. It also notes other physical hazard families, such as geological hazards, that may need to be considered to enable a comprehensive assessment of physical risk, even where they are conceptually distinct from climate- and nature-related drivers.

Outlook: Integrating nature-related physical risks

The hazard taxonomy used in this paper focuses primarily on climate-related physical hazards. However, physical risks are not driven by climate alone. Changes in the condition of ecosystems, water systems, soils and biological resources can materially increase the severity of physical impacts and create additional pathways through which environmental change affects economic activity.

Nature enters the physical risk framework through two complementary mechanisms: the amplification of existing physical hazards and the emergence of additional nature-related hazards, as illustrated below:

Figure 2: Nature enters framework through amplification and additional hazards



One way to make these relationships explicit is to distinguish between **physical hazards** and the broader **state of nature / earth system** within which those hazards occur. Under such an approach, conditions such as ecosystem integrity, water availability, soil condition, biodiversity loss and pollution levels are treated as environmental conditions that influence the frequency, severity and consequences of physical hazards.

Nature-related degradation can amplify familiar climate-related hazards. For example, degradation of wetlands, catchments and natural water-storage systems can reduce water retention and natural flood regulation, increasing the severity of flooding. Deterioration of water resources can amplify water stress and drought impacts by reducing the availability of usable freshwater. Soil degradation can increase susceptibility to drought and reduce agricultural resilience. Ecosystem degradation can increase the vulnerability of biological production systems to pest outbreaks, disease and pollination failure. Nature therefore affects physical risk not only through additional hazards, but also by changing how existing hazards propagate and materialise.

In addition, some nature-related physical risks may arise through hazard families that are not explicitly represented within climate-focused hazard frameworks. Particularly relevant examples include:

Biological and ecosystem-related hazards, such as pest infestations, plant disease outbreaks, pollination failure, reduced biomass availability and reductions in genetic-resource availability, and **Pollution-related hazards,** including air-quality degradation, water contamination and soil contamination.

These hazards are particularly relevant for activities that depend heavily on water, labour, environmental quality or biological production systems. They are also important for food and soft-commodity value chains, where disruption of agricultural and biological inputs may propagate through supply chains and affect counterparties far beyond the point where the original physical impact occurs.

As a result, future approaches to physical risk assessment are likely to increasingly consider both climate-related hazards and the condition of underlying natural systems. A broader perspective that incorporates the state of nature / earth system can help make climate-nature interactions, amplification effects and additional nature-related hazards more explicit within physical risk assessment frameworks.

Finally, a comprehensive physical risk assessment should extend beyond climate- and nature-related hazards to consider geological hazards, such as earthquakes, tsunamis and volcanic activity. These fall outside the climate-related EU Taxonomy hazard framework and are conceptually distinct from the mechanisms discussed above.

2.2. Product taxonomy

The following banking products and activities were identified as among those most likely to be impacted by physical risks or particularly relevant for physical risk assessment. The subsequent modelling discussion focuses primarily on corporate and real estate exposures, where physical risk is regarded as particularly material and modelling approaches are more advanced.

Table 2: List of banking business line products.

Residential Real Estate
Commercial Real Estate (Asset Backed)
Project Finance
Small & Medium-Sized Business / Business Banking
Large Corporates
Investment Management / Own Operations
Other: Financial Institutions, Sovereigns, Trading-Book

For physical risk assessment, the banking product provides the context for the exposure, while the **underlying entity or asset type is important in determining the physical transmission pathways that need to be considered.** The products and activities listed above can broadly be related to four underlying entity types: **real estate, corporates, government entities and financial institutions.**

Residential and commercial real estate exposures are assessed in relation to the underlying properties. Project finance, SME/business banking and large corporate exposures require consideration of the relevant corporate entity and the pathways through which physical hazards may affect its assets, operations, external dependencies and markets. Sovereign and other public-sector exposures require consideration of impacts on government entities, including through fiscal and macro-economic pathways, while exposures to financial institutions require consideration of their underlying portfolios, assets and broader economic and financial conditions.

Investment-management and trading-book activities may contain a mixture of corporate, real estate, government and financial-institution exposures. The relevant physical transmission pathways therefore depend on the underlying holdings rather than the portfolio label itself.

A bank's own operations are treated similarly to corporate activities for the purpose of identifying physical transmission pathways. Physical hazards may affect the bank's own assets and operations, including through disruption to premises, employees and the infrastructure and services on which banking activities depend.

The underlying entity or asset type thus provides the link between the product taxonomy and the physical transmission framework developed in Chapter 3, which describes how hazards affect these different entities and assets and translate into financial outcomes.

2.3. Use-case taxonomy

Physical risk assessments support a range of banking decisions and risk-management activities. The **use case describes the purpose for which the assessment is performed** and therefore influences the required granularity, time horizon, level of aggregation, type of output, and treatment of uncertainty.

At exposure level, physical risk assessment can support **credit granting, ESG assessment and origination** by identifying material physical risks affecting an individual counterparty or asset and considering relevant adaptation and resilience measures. **Collateral valuation** focuses on the implications of physical risk for the current and future value of assets securing an exposure. **Customer engagement** uses the assessment to identify material sources of physical risk and support discussion of risk reduction, adaptation and resilience.

At portfolio level, **portfolio and sector analysis** aggregates physical risk information across exposures to identify patterns and concentrations by, for example, sector or geography. **Risk appetite setting** uses such information to define and monitor the level and distribution of physical risk a bank is prepared to accept. **Pillar 3 reporting** uses physical risk assessments to support regulatory disclosure of climate-related risks and exposures.

Scenario-based applications assess how risks may develop under specified future conditions. **ICAAP** uses physical risk analysis as part of the bank's assessment of risks to capital and capital adequacy. **Regulatory climate stress testing** assesses the resilience of exposures and portfolios under prescribed adverse climate scenarios, while broader **scenario analysis** can be used to explore the consequences of alternative physical risk conditions and assumptions. **IFRS 9 provisioning** concerns the incorporation of relevant physical risk effects into forward-looking credit risk assessment and expected credit loss where these risks are material.

Other applications include **physical risk in investment modelling**, where physical risk is assessed in relation to bonds, equities and real assets; the **Green Asset Ratio**, where physical risk and climate adaptation considerations may form part of the relevant regulatory assessment; and **operational risk management**, where institutions assess how physical hazards may disrupt their own premises, people, infrastructure dependencies and banking activities.

Table 3: Key banking use cases for physical risk assessment

Exposure-based	Credit granting, ESG assessment and origination
	Collateral valuation
	Customer engagement
Portfolio-based	Portfolio/sectorial analysis
	Risk Appetite Statement
	Pillar 3 Reporting
Scenario-based	ICAAP
	Regulatory climate stress tests
	Scenario analyses
	IRFS9 provisioning
Other	Physical Risk in Investment Modelling (investment analysis on bonds, equities and real assets)
	Green asset ratio
	Operational risk management

The table above groups these use cases according to broad assessment perspectives – exposure-based, portfolio-based and scenario-based – consistent with the methodological groupings used by the EBA Guidelines on ESG Risk Management [6], together with several additional applications. These groupings indicate the primary assessment perspective associated with each use case and should not be interpreted as mutually exclusive methodological categories. Exposure- and portfolio-level assessments may also be forward-looking and scenario-based, while scenario-based assessments may incorporate detailed exposure- and portfolio-level information.

The intended use case helps determine **how the assessment needs to be performed and what it needs to produce**, but does not by itself determine the physical transmission pathways or modelling approaches required. These depend also on the underlying exposure and the mechanisms through which physical hazards may affect it. Chapter 3 develops these transmission pathways, while Section 3.4 explains how the relevant pathways and intended use together inform the selection of modelling approaches.

2.4. Banking transmission channel taxonomy

Physical risk can lead to financial loss for banks through different banking transmission channels. The taxonomy below identifies three broad transmission-channel families – collateral devaluation, deterioration of client financial strength and devaluation of assets held by the bank – leveraging the microeconomic and macro-economic channels referenced in the EBA Guidelines on Environmental Scenario Analysis [7], p.37.

Table 4: Key banking transmission channels

	BANKING TRANSMISSION CHANNEL FAMILY	MAPPING TO EBA TAXONOMY	DESCRIPTION
Collateral Devaluation	Market Value Change	• Profitability Impact • Household Income Impact • Asset Damage & Rebuild Debt	Devaluation of collateral, giving rise to higher loss given default, as a result of a climate-related change in the market value of (undamaged) assets.
	From Asset Impairment	• Profitability Impact • Household Income Impact • Asset Damage & Rebuild Debt	Devaluation of collateral, giving rise to higher loss given default, as a result of damage sustained to asset and/or degradation in condition of surroundings.
Deterioration of Client Financial Strength	For Business Entities	• Profitability Impact • Asset Damage & Rebuild Debt • Macro Knock on Effects • Supply Shock Inflation • Workforce Productivity & Health • Supply Chain & Scarcity	Deterioration of company financial strength from impact on cashflows, resulting in change in client probability of default.
	For Individuals	• Macro Knock on Effects • Migrations and displacements • Workforce Productivity & Health	Deterioration of client financial strength from impact on individual's income and outgoings, resulting in change in client probability of default.
Devaluation of Assets Held by the Bank	Market Driven	• Profitability Impact • Macro Knock on Effects	Devaluation of asset, causing direct loss, as a result of a climate-related change in the market value of (undamaged) assets.
	From Asset Impairment	• Profitability Impact • Asset Damage & Rebuild Debt	Devaluation of asset, causing direct loss, as a result of damage sustained to asset and/or degradation in condition of surroundings.

These banking transmission channels describe the **routes through which the financial consequences of physical risk enter the bank's risk position.** For lending exposures, physical risk may weaken a borrower's financial strength and thereby affect creditworthiness and probability of default (PD). Where an exposure is secured, physical risk may also reduce the value of collateral and thereby affect loss given default (LGD). Where the bank itself holds an affected asset, changes in its value may result in a direct valuation loss.

Physical risk may also affect a bank through **disruption of its own operations**, for example through impacts on its premises, workforce or dependencies on infrastructure and services. These operational impacts are considered separately in Chapter 3 and should not be interpreted as part of the asset-devaluation channel.

The banking transmission channels describe the financial-risk end of a broader transmission process. They should therefore be distinguished from the underlying **physical transmission pathways** through which hazards affect assets, counterparties and economic activity before translating into financial outcomes. Chapter 3 develops these physical transmission pathways and explains how they connect physical hazards to financial outcomes and, ultimately, to the banking transmission channels defined here.

3. PHYSICAL RISK TRANSMISSION FRAMEWORK

This chapter sets out the **physical transmission pathways** through which physical hazards affect different entities and assets and translate into operational and financial outcomes. It focuses primarily on corporates and real estate, with a high-level discussion of government entities and financial institutions, before bringing the framework elements together to consider how an appropriate modelling approach can be selected.

As introduced in Section 2.2, the relevant physical transmission pathways depend on the **underlying entity or asset being assessed.** Physical hazards affect corporates, real estate, government entities and financial institutions through different mechanisms. The entity or asset underlying the banking exposure therefore provides the starting point for identifying the relevant transmission pathways.

A distinction is made between **physical transmission pathways** and the **banking transmission channels** introduced in Section 2.4. Physical transmission pathways describe the causal mechanisms through which hazards affect an entity or asset and translate into operational and financial outcomes. Banking transmission channels describe how those resulting financial outcomes or asset-value effects enter the bank's risk position, for example through deterioration of client financial strength, collateral devaluation or changes in the value of assets held by the bank.

At the level of individual assets and activities, physical impacts can broadly take the form of **damage or disruption.** Damage refers to physical impairment of an asset. Disruption refers more broadly to impairment of the function or activity supported by an asset, resource or workforce and does not necessarily require physical damage. For corporates, disruption may affect operational capacity, production or costs; for real estate, analogous impacts include impairment of functionality, habitability or occupant comfort. These physical and operational impacts provide the starting point for their subsequent translation into financial outcomes.

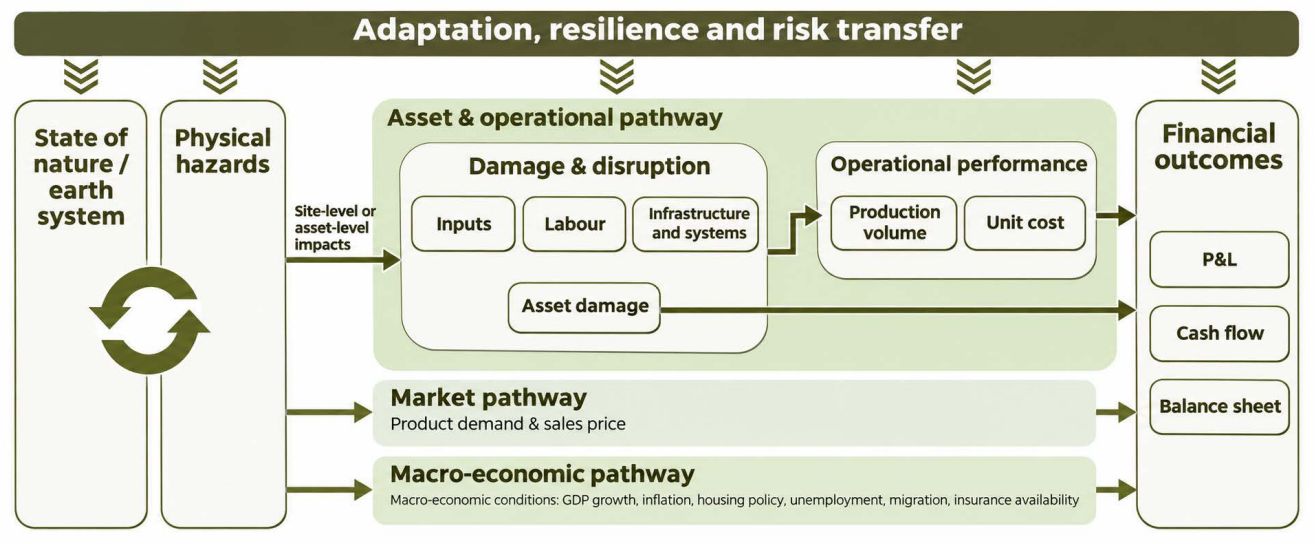
Location-specific impacts on physical assets are an important component of physical risk assessment, but do not capture the full range of mechanisms through which physical hazards may affect an entity. Corporates may also be affected through disruption of external inputs, infrastructure and other operational dependencies, changes in demand and market conditions, and broader macro-economic effects. Real estate may similarly be affected through both realised or anticipated property-level impacts and wider market and macro-economic developments. Several transmission pathways may therefore be relevant to the same entity, exposure or physical hazard.

The sections that follow develop these transmission pathways for **corporates and real estate**, before providing a high-level overview for **government entities and financial institutions.** Section 3.4 then brings the framework together to consider what needs to be modelled and how the modelling approach should be tailored to the intended use.

3.1. Corporates

The below sets out how physical hazards transmit to company financial outcomes.

Figure 3: Transmission of physical climate and nature-related hazards to company-level financial outcomes



As discussed in the *Outlook:* Integrating Nature-Related Physical Risks box, physical hazards arise within a broader state of nature and earth system shaped by climate change, ecosystem condition and other environmental drivers. Changes in the state of nature and earth system can generate or amplify physical hazards.

The figure above illustrates how physical hazards affect company financial outcomes through three pathways.

The **asset & operational pathway** captures the effects of physical hazards on assets, inputs, labour and infrastructure required to sustain operations. These impacts affect operational performance through changes in production and distribution volume and unit cost before ultimately affecting financial outcomes. Damage to assets also transmits directly to financial outcomes: it leads to lower asset values and/or requires expenditure of repair or replacement.

The **market pathway** captures changes in product demand and realised sales prices resulting from physical hazards. These effects may arise even where a company experiences limited direct operational disruption. Examples include changes in demand for particular products and services following physical events (e.g. air conditioning units due to a heatwave), or changes in market prices resulting from physical disruptions to production elsewhere.

The **macro-economic pathway** captures broader economy-wide effects arising from physical hazards, including changes in economic growth, inflation, funding and financing conditions, and sectoral activity. These effects may influence financial outcomes independently of company-specific operational impacts. The asset & operational pathway is particularly important for understanding how physical hazards affect individual counterparties and is therefore described in more detail below.

Scope convention

Some institutions use a three-scope convention to describe the origin of impacts within the transmission pathways above. Under this convention:

- **Scope A** covers asset damage and operational impacts arising at the counterparty's own sites, including impacts on locally dependent inputs, labour capacity and infrastructure and systems;
- **Scope B** covers off-site operational impacts arising through external inputs, labour, infrastructure and systems on which the counterparty depends; and
- **Scope C** covers impacts arising through the market and macro-economic pathways.

This convention provides a useful way of describing where impacts originate, but does not replace the transmission-pathway framework used in this paper. In particular, the distinction between on-site and off-site impacts should not be interpreted simply as a distinction between "direct" and "indirect" impacts: disruption to a critical supplier, infrastructure system or other off-site dependency may transmit directly into the counterparty's operations.

Asset & operational pathway

Physical hazards may affect companies both at their own operational sites and through dependencies beyond the site boundary. Site-level impacts arise where hazards affect a company's own assets, workforce and locally sourced inputs (e.g., water). Off-site impacts arise where hazards affect suppliers, biological production systems, transport infrastructure, energy systems, labour markets or other external dependencies on which operations rely.

Whether a hazard occurs at an operational site or elsewhere, it ultimately affects operations through the same operational impact channels:

- **Inputs:** Reduction in availability or usability of required inputs (e.g. water, energy, raw materials), or increased cost thereof.
- **Labour capacity:** Reduction in labour productivity, availability or increase in labour costs. Impacts may arise e.g. through heat stress, occupational health & safety restrictions, reduced working hours, illness or injury.
- **Infrastructure and systems:** Disruption to transport or enabling systems (e.g., power, telecommunications).
- **Asset damage:** Structural damage or degradation of an asset which reduces functionality or useable lifespan.

For example, drought may affect water availability at the company's own site or at a supplier location. Flooding may disrupt transport infrastructure serving a site or reduce labour availability where employees are unable to travel to work, even without affecting the production site itself.

The operational impact channels describe the operational dependencies affected rather than the specific nature of the impact itself. Depending on the hazard and activity, impacts may arise through increased demand for resources or services, reduced availability, quality or capacity, or increased operating costs associated with maintaining operations. For example, a heatwave may increase demand for water, cooling and labour. Drought may reduce water availability. Disruption of a transport corridor may increase logistics costs while leaving physical assets unaffected.

As a result, **physical hazards should be assessed at the location of the relevant dependency** rather than solely at the location of the company's own facilities. Depending on the operational impact channel

being assessed, the relevant location may be the operational site, a supplier location, a water basin, an electricity network, a logistics network or a regional labour market.

Operational performance

Disruption from physical hazards affects company performance through two primary mechanisms:

- **Production and distribution volume,** reflecting the company's ability to produce and deliver goods and services.
- **Unit cost,** reflecting the cost of producing and distributing each unit of output.

IImpacts on inputs, labour capacity and infrastructure and systems may reduce production and distribution volume by limiting operational capacity or interrupting business activities. The same impacts may increase unit costs through higher input prices, increased resource requirements, additional labour expenditure, alternative logistics arrangements, business continuity measures or reduced operational efficiency.

Asset damage is distinct from the other operational impact channels because it affects financial outcomes through two transmission pathways. First, asset damage may impair production and distribution capacity, affecting output volumes and unit costs in the same way as impacts on inputs, labour capacity and infrastructure and systems. Second, asset damage may give rise directly to financial consequences associated with repair or replacement cost for damaged assets or decline in asset value.

Financial outcomes

The asset & operational, market and macro-economic pathways affect financial outcomes through changes in revenue, costs, investment requirements, cash generation and financial resilience.

Profit and loss (P&L) is affected through changes in revenue and costs.

Revenue is affected primarily through production and distribution volume, product demand and realised sales prices. Physical hazards may reduce output, interrupt service delivery or affect demand conditions, resulting in lower sales volumes or reduced pricing power. Physical hazards may also increase demand or realised sales prices for particular products and services where scarcity, recovery or reconstruction activity increases market demand.

Costs and investment expenditure are affected through two distinct mechanisms. First, operational impacts may increase unit costs through higher input prices, increased resource requirements, additional labour expenditure, alternative logistics arrangements, business-continuity measures or reduced operating efficiency. Second, physical hazards may create additional expenditure that is not directly linked to unit production costs. Examples include repair and recovery costs following asset damage. Unlike the unit cost effects described above, these expenditures arise directly from asset damage or from adaptation and resilience measures intended to reduce future disruption and losses. Depending on the nature of the expenditure, they may be recognised as operating expenditure, investment expenditure, or both.

Cash flow is affected by the combined effects of changes in revenue, costs and investment expenditure. Revenue losses reduce cash inflows, while higher operating costs, repair costs and investment requirements increase cash outflows. Timing mismatches between these effects may create liquidity pressures.

Balance sheet effects may arise through changes in profitability, cash generation, asset condition, asset values, leverage, working capital requirements and financing conditions. Asset damage may directly impair asset values, while sustained impacts on profitability and cash flow may weaken financial resilience and debt-servicing capacity.

Collectively, the operational, market and macro-economic pathways determine how physical hazards and adaptation and resilience measures affect company financial outcomes and financial strength. Physical hazards may weaken revenues, increase costs and impair financial resilience, while adaptation and resilience measures aim to preserve operational performance and reduce the resulting financial impacts.

Adaptation, resilience and risk transfer

These measures can address different stages of the transmission pathway:

1. **Hazard reduction:** reducing the severity or frequency of hazards, for example through watershed restoration, wetland restoration, flood-retention areas, coastal ecosystem restoration and other nature-based solutions.
2. **Exposure reduction:** reducing the exposure of people, assets and activities to hazards through e.g. land-use planning, relocation, asset siting decisions and flood protection.
3. **Impact reduction:** reducing the extent to which hazards translate into physical or operational impacts, for example through asset hardening, resilient building design, flood-proofing, enhanced cooling systems, drought-resistant crop varieties, monitoring systems and early-warning capabilities.
4. **Dependency and continuity management:** maintaining access to critical resources, infrastructure and services during disruption, for example through water recycling and reuse, alternative water sources, supplier diversification, logistics redundancy, backup systems and business continuity planning.
5. **Financial resilience:** reducing the financial consequences of impacts through insurance, risk-transfer mechanisms, contingency funding and recovery planning.

Adaptation and resilience measures may reduce operational disruption, preserve production and distribution volumes, maintain access to critical resources and services, limit increases in operating costs, reduce asset damage, or reduce the financial consequences of physical hazards once they occur.

Many adaptation and resilience measures require investment and may therefore increase operating and/or capital expenditure. Such measures may increase costs in the short term while reducing the expected operational and financial consequences of future physical hazards.

The most appropriate adaptation response depends on the hazards involved, the assets, operations and dependencies affected, and the vulnerability of the counterparty or property. Adaptation and resilience measures should also be assessed for their effectiveness under future climate and environmental conditions, as well as their expected resilience benefits relative to implementation costs.

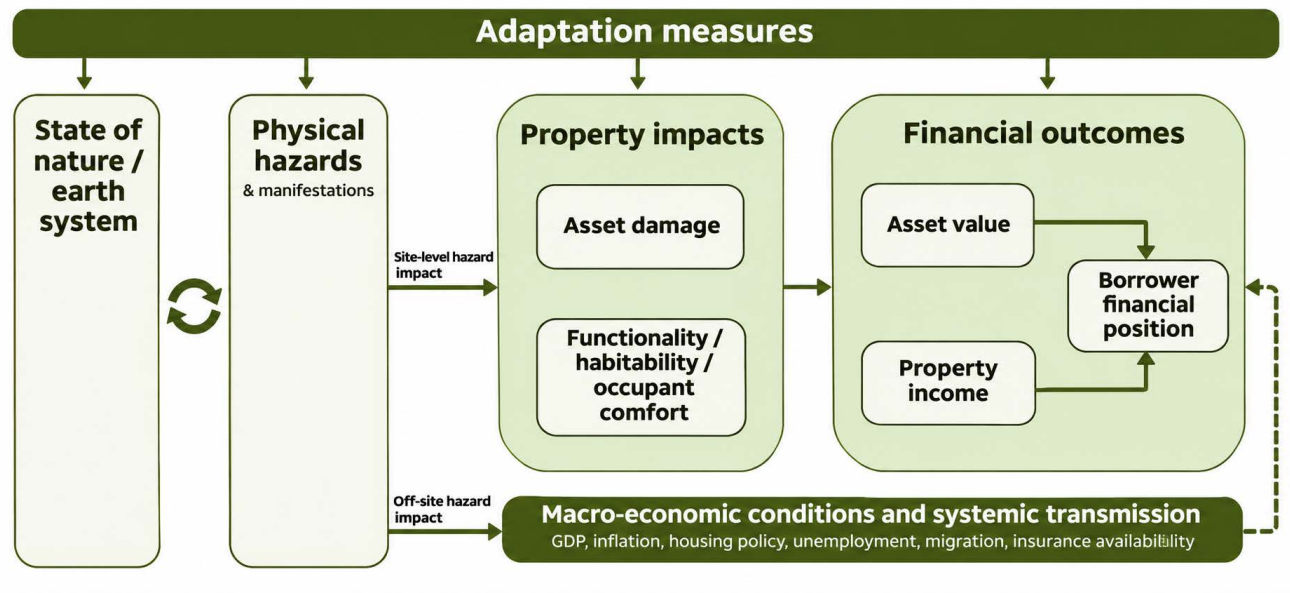
Insurance and other risk-transfer mechanisms may reduce the financial consequences of some physical impacts, but coverage may be incomplete and future availability and affordability uncertain, particularly as physical risks increase. These limitations should be considered when assessing the residual financial risk faced by a counterparty.

3.2. Real estate

The real estate section assesses physical risks from the perspective of the property as an asset, rather than the activities conducted within the property. It therefore applies to owner-occupied residential and income-producing real estate exposures. Where real estate serves solely as collateral for a corporate exposure, physical risk is assessed primarily through the corporate transmission framework.

The figure below illustrates how physical hazards affect real estate assets and their owners.

Figure 4: Transmission of physical hazards to real estate asset value, property income and borrower financial position



As discussed in the Outlook: Integrating Nature-Related Physical Risks box, physical hazards arise within a broader state of nature and earth system shaped by climate change, ecosystem condition and other environmental drivers. Changes in the state of nature and earth system can generate or amplify physical hazards. These hazards affect real estate through both site-specific property impacts and broader market and macro-economic pathways. Together, these transmission mechanisms can affect asset values, property income and borrower financial position. Within the banking transmission-channel taxonomy, the resulting effects may thus materialise through collateral devaluation, deterioration of client financial strength or devaluation of assets held by the bank, depending on the nature of the exposure.

Site-specific property impacts

At the property level, physical hazards may result in either asset damage or deterioration in functionality, habitability and occupant comfort.

Asset damage refers to impairment of the physical fabric, structure or systems of a property and may range from minor repairable damage to partial or, in extreme cases, total loss of the asset. Examples include flooding, wildfire damage, wind damage, coastal erosion and structural damage resulting from ground movement. This corresponds to the *From Asset Impairment* category within the banking transmission channel taxonomy and may give rise to repair, reconstruction and adaptation expenditure borne by the owner or borrower.

Functionality, habitability and occupant comfort refer to the extent to which a property remains suitable for its intended use, independent of direct physical damage to the asset itself. Examples include the ability to maintain acceptable indoor temperatures, air quality, water availability and access to essential services. These impacts may arise from hazards such as extreme heat, extreme cold, water stress, drought, water quality deterioration, air pollution and wildfire smoke exposure.

Unlike asset damage, these impacts primarily affect the usability, attractiveness and operational suitability of a property rather than its physical integrity. They may nevertheless influence asset values, property income and borrower financial position through adaptation requirements, operating costs, insurance costs, market attractiveness, tenant demand and occupier preferences. These mechanisms are closely aligned with the *Market Value Change* and *Market Driven* categories in the banking transmission channel taxonomy, whereby asset values may change even in the absence of realised physical damage.

Both asset damage and impacts on functionality, habitability and occupant comfort may be actual or expected. Anticipated future damage, reduced functionality or increasing adaptation requirements may affect asset values, property income and borrower finances even before significant physical impacts are observed. As a result, devaluation may arise both from realised asset impairment and from market expectations regarding future risk, adaptation requirements, insurability and long-term attractiveness.

Market and macro-economic transmission

Physical hazards may also affect real estate through both property-specific and broader market and macro-economic pathways. Relevant mechanisms include changes in insurance availability and affordability, migration patterns, housing and property demand, inflation, labour markets and other macro-economic conditions. These correspond to broader *Macro Knock-on Effects* in the EBA transmission taxonomy. These factors can influence real estate values, rental markets and borrower finances even where a property experiences limited direct physical impacts.

Asset value

Physical hazards may reduce real estate asset values through both direct and indirect mechanisms. Asset damage can reduce market value where damage is unrepaired or where residual impacts remain. Asset values may also decline due to expected adaptation and retrofit costs, reduced functionality, reduced habitability or occupant comfort, and changing perceptions of the long-term attractiveness or resilience of a property. These pathways are consistent with the market-value-based mechanisms described within the banking transmission channels for *collateral devaluation* and *devaluation of assets held by the bank*.

Broader market and macro-economic effects may further affect asset values through changes in insurance markets, migration patterns, property demand and wider developments in real estate markets.

Property income

For income-producing real estate, physical hazards may affect the ability of a property to generate income. Asset damage may result in business interruption, lower occupancy or reduced rental income, while reduced functionality, habitability or occupant comfort may reduce tenant demand and the attractiveness of the property. Physical hazards may also increase operating costs, adaptation expenditure and insurance costs associated with the property. This represents the real-estate equivalent of *Profitability Impact*, affecting asset performance through changes in rental income, occupancy and operating costs.

Property income may additionally be affected by broader market and macro-economic factors, including changes in local economic conditions, tenant demand, demographic trends and insurance availability.

Borrower financial position

Physical hazards ultimately affect borrower financial position through their impact on asset values, property income and expenditure.

For owner-occupied residential properties, borrower finances may be affected through repair costs, insurance premiums, adaptation expenditure, utility costs and broader impacts on household income and expenditure. This corresponds closely to the EBA category *Household Income Impact*.

For income-producing real estate, borrower finances may be affected through changes in rental income, occupancy rates and operating costs, as well as repair, insurance and adaptation expenditure.

Macro-economic effects may further affect borrower finances through impacts on employment, inflation, financing conditions and wider economic activity. These effects provide an additional route through which *Household Income Impact* and *Macro Knock-on Effects* influence borrower affordability and repayment capacity.

Adaptation, resilience and risk transfer

Adaptation and resilience measures can reduce both asset damage and impacts on functionality, habitability and occupant comfort. They may also help maintain or enhance asset values by improving resilience to physical hazards, reducing expected future losses and supporting the attractiveness of properties exposed to physical risks.

Insurance can mitigate part of the financial impact of hazard-related asset damage, although increasing premiums or reduced insurance availability may themselves constitute important drivers of financial impact.

3.3. Other entity types

The following sections provide a high-level overview of physical risk transmission for government entities and financial institutions. These entity types are included to complete the transmission framework but are not the primary focus of the detailed modelling guidance in this paper.

3.3.1. Governments

This section applies to sovereigns, sub-sovereigns, municipalities and supranational entities, including government lending exposures and sovereign bond holdings. Physical hazards can affect government entities through both direct fiscal impacts and broader macro-economic effects. Government entities are not a primary focus of the detailed modelling guidance in this paper, and methodologies for assessing their physical risk remain less mature than for corporate and real estate exposures. The discussion here therefore provides a high-level overview of the principal transmission pathways.

Direct fiscal impacts arise where physical hazards reduce tax revenues and increase public expenditure. Lower tax revenues may result from damage to assets, operational disruption, reduced economic activity, and lower household or corporate income. At the same time, governments may face higher expenditure associated with emergency response, reconstruction, social support, infrastructure repair and adaptation measures. Together, these effects may weaken fiscal balances and increase funding requirements.

Physical hazards may also affect government entities through broader impacts on economic activity, productivity, employment, inflation and investment. These macro-economic effects can influence public finances through changes in tax revenues, public expenditure, debt dynamics and borrowing costs. For sovereign bond exposures, market perceptions of fiscal sustainability and economic resilience may affect sovereign creditworthiness and bond valuations.

3.3.2. Financial institutions

Physical risk to a bank's **own operations** can be assessed in the same way as the operations of a corporate, considering potential impacts on its premises, workforce and dependencies on infrastructure and services.

The assessment of a financial institution as a **counterparty or investment** is different. Physical impacts on the institution's own premises and operations will generally capture only a limited part of its overall physical risk. A substantial part of the risk arises through its lending, investment and insurance activities and therefore reflects the physical risks affecting the underlying counterparties and assets.

For lending and investment portfolios, the relevant physical impacts originate through the transmission pathways described in the preceding sections. For example, physical hazards may weaken corporate counterparties through asset and operational, market and macro-economic pathways, or affect real estate exposures through property-level impacts and changes in property values and income. For the financial institution, these effects may translate into deteriorating credit quality, reduced collateral values, investment losses, changing market valuations or increased insurance claims. As a result, the physical risk profile of a financial institution is strongly influenced by the assets, sectors and counterparties to which it is exposed.

In principle, these risks could be assessed by looking through to the underlying exposures and applying the relevant transmission framework. In practice, sufficiently detailed information on the composition,

location and physical risk characteristics of an external financial institution's underlying exposures may not be available to the assessing institution. Assessment may therefore need to rely on more aggregated information on portfolio composition and sectoral or geographic exposures.

Financial institutions may also be affected through market and macro-economic pathways that operate across portfolios and the wider financial system. Physical hazards may affect economic growth, employment, inflation, public finances, asset prices and financial-market conditions. These effects may influence portfolio performance, funding conditions, asset valuations and profitability, including where individual underlying exposures experience limited direct physical impacts.

Deterioration in sovereign creditworthiness may similarly transmit through financial markets and financial institutions, for example through changes in sovereign asset valuations, funding conditions and the broader economic and financial environment.

3.4. Physical risk modelling: selecting an appropriate modelling approach

The preceding sections describe the different pathways through which physical hazards can affect entities and assets and translate into financial outcomes. Translating these pathways into a physical risk assessment requires decisions about what needs to be modelled, how it should be modelled for the intended use, and where proxies may be appropriate.

There is therefore no single modelling approach that is appropriate for all physical risks or banking applications. The appropriate approach depends first on the underlying entity or asset and the material transmission pathways through which it may be affected. It also depends on the intended use of the assessment, which determines the required level of specificity, coverage, time horizon and aggregation. Where the information or relationships required for the assessment cannot be represented directly, proxies may be used to address specific gaps.

The following sections set out these considerations in turn.

3.4.1. Determining what needs to be modelled

Before selecting a modelling approach, it is necessary to determine **what the assessment needs to capture**. This requires consideration of the entity or asset being assessed, the relevant banking transmission channel or risk outcome, the physical hazards to which the entity or asset and its dependencies may be exposed, and the transmission pathways through which those hazards could drive the relevant outcome.

The **entity or asset and the banking transmission channel** provide the starting point for determining the scope of the assessment. Different entity types are affected through different physical transmission pathways, while the banking transmission channel determines which resulting effects need to be followed through to the bank. For example, an assessment of deterioration in a corporate client's financial strength needs to consider the pathways through which physical hazards could materially affect the client's financial performance. An assessment of collateral devaluation instead focuses on the pathways through which physical risk could affect the value of the collateral asset.

The assessment then needs to identify the **relevant hazards and locations** at which to assess hazard exposure. These depend on the characteristics of the entity or asset and the locations at which relevant impacts may arise. For corporates, this may extend beyond their own operational sites to the locations of material suppliers, inputs, water resources, infrastructure or other dependencies. For real estate, the property location will generally provide the primary location for assessing relevant hazards. Some hazards are also limited to particular geographic settings.

Finally, the assessment should identify the **physical transmission pathways** through which those hazards could materially affect the entity or asset and contribute to the relevant banking transmission channel or risk outcome. More than one pathway may be relevant. For example, deterioration in a corporate client's financial strength may result from site-level or off-site operational impacts, market effects or broader macro-economic effects.

The relevant physical transmission pathways should be considered together rather than treated as alternative modelling perspectives associated with particular use cases. For example, a corporate counterparty may be affected simultaneously by physical impacts at its own facilities, disruption of critical suppliers or infrastructure, changes in market conditions and broader macro-economic effects. Where these pathways are material to the banking transmission channel or risk outcome being assessed, they form part of the assessment irrespective of whether the ultimate use is an exposure-level decision, portfolio analysis or scenario-based assessment.

The purpose of this step is thus to establish the relevant scope of physical risk transmission before considering how that scope should be modelled for a particular use case.

3.4.2. Ensuring consistency across modelling components

Where several physical transmission pathways are assessed together, the different modelling components should represent a common and internally consistent physical risk situation. This applies whether the assessment is based on an observed historical event, current conditions or a forward-looking scenario. A common basis does not require all transmission pathways to be assessed within a single integrated model. Site-level impacts, off-site operational transmission, market effects and macro-economic impacts may be assessed using different methods and levels of granularity. The modelling components should nevertheless be consistent in the physical conditions they represent and, where relevant, in the associated economic and other assumptions.

Depending on the assessment, relevant assumptions may include:

- the physical hazards being assessed, including their location, severity and timing;
- the **time horizon over which impacts are assessed**;
- for forward-looking assessments, the underlying climate and socioeconomic conditions; and
- adaptation and resilience measures, insurance coverage, policy intervention and the pace of recovery.

For example, an assessment of a flood event may combine estimates of damage and operational disruption at individual sites, disruption of critical suppliers or infrastructure, market effects and broader macro-economic impacts. Although these effects may be modelled using different techniques, they should relate to the same underlying event and compatible assumptions about its consequences and recovery.

Where several transmission pathways are assessed together, the modelling components should be aligned to the same assessment horizon. This is important because physical, operational, market and macro-economic effects may develop over different timescales, while the outputs need to describe a coherent physical risk situation.

For forward-looking assessments, the future physical risk conditions being assessed should also be clearly specified. These may reflect different assumptions regarding future warming or climate conditions, socioeconomic development, adaptation and resilience, policy intervention and other relevant scenario variables. Physical risk estimates should therefore be interpreted as conditional on the climate and socioeconomic assumptions applied, rather than as predictions of a single expected future state.

Common scenario frameworks can provide a connecting structure across modelling components. The NGFS scenarios, for example, provide common narratives and sets of climate-related and macro-financial variables that can support consistency across different modelling approaches [8]. Similarly, the Federal Reserve's pilot climate scenario analysis provided participating institutions with defined climate, economic and financial scenario variables for exploratory assessment [9].

3.4.3. Tailoring the modelling approach to the use case

Once the relevant hazards and physical transmission pathways have been identified, the modelling approach should reflect the **intended use of the assessment**. Different use cases place different requirements on the level of specificity, coverage, time horizon and aggregation of the analysis. These requirements affect how the relevant transmission pathways are represented and the extent to which simplification or proxy information may be appropriate.

For **exposure-level use cases**, such as credit granting, collateral valuation and customer engagement, greater counterparty- or asset-level specificity is generally required. The assessment should provide sufficient understanding of the **mechanisms through which the material physical risks arise and translate into impacts on the specific entity or asset.** For site-level impacts, this means understanding the relevant hazard, exposure and vulnerability and the resulting physical or operational impact, rather than relying solely on a proxy for the eventual financial effect. The same principle applies to other material transmission pathways: where off-site dependencies, market effects or other pathways are important to the entity, the assessment should seek to understand how these effects arise and transmit to the entity.

This level of understanding is particularly relevant where the assessment is intended to support decisions about an individual exposure, including the identification and assessment of adaptation, resilience or other risk-mitigation measures. The relevant analysis is not limited to site-level asset damage. Depending on the characteristics and business model of the entity, material impacts may arise through its own assets and operations, external dependencies, markets and broader economic conditions, and several pathways may need to be considered together.

For **portfolio-level use cases**, such as portfolio and sector analysis, screening and prioritisation, risk appetite and disclosure, the emphasis shifts towards **consistent coverage, comparability and aggregation across a potentially large number of exposures.** The assessment still needs to identify the principal drivers of physical risk, for example the sectors, regions, hazards or transmission pathways contributing materially to portfolio risk. However, the level of counterparty- or asset-specific detail required may be lower where the objective is to understand the distribution and magnitude of risk across a portfolio rather than to identify an exposure-specific risk-management response.

Detailed exposure-level modelling can still form the basis of a portfolio assessment where sufficiently granular information and models are available, with the resulting impacts aggregated across exposures. Where such information is incomplete or the required coverage makes this impracticable, greater simplification and use of proxies may be appropriate. Portfolio-level assessment should therefore not be understood as a separate type of physical risk model, but as an application that may combine granular modelling and more simplified approaches according to the information available and the purpose of the assessment.

Where the required output is itself sectoral, regional or economy-wide, an aggregate or reduced-form model may be appropriate in its own right; such models should not be interpreted as substitutes for counterparty-specific transmission modelling where exposure-level insight is required.

The appropriate **time horizon** also depends on the intended use. Scenario and stress-testing applications may assess medium- to long-term physical risk developments under specified future conditions, while strategic applications may require longer horizons to capture structural changes in hazards and economic conditions.

For exposure-level assessments, the relevant horizon depends on the banking transmission channel and the decision being supported. For collateral devaluation, relevant horizons may include both the duration of the loan, over which the bank remains exposed to loss, and the expected lifetime of the asset, since anticipated future physical impacts and adaptation requirements may affect asset value before those impacts are realised. For assessments of corporate financial strength, relevant horizons may include the duration of the loan and the expected duration of the client relationship.

Portfolio-level assessments may apply different horizons according to their purpose and may aggregate exposures with different remaining maturities or asset lives. In all cases, model outputs should be interpreted in relation to the time horizon and assumptions for which they were produced.

Across all use cases, the modelling approach should retain the material physical transmission pathways identified in Chapter 3. The use case determines **the depth, granularity and coverage with which those pathways need to be modelled.** Where direct information or sufficiently granular modelling is unavailable or disproportionate to the intended use, proxies can be used to address specific gaps within the assessment.

3.4.4. Use of proxies

Physical risk assessments frequently face gaps in the information or relationships required to model the relevant transmission pathways directly. **Proxies can be used to represent specific missing inputs, characteristics or relationships within an assessment.** Proxy use should therefore not be regarded as a separate modelling approach: proxies may be used within different modelling approaches and at different stages of the transmission chain.

The role and extent of proxy use depend on the intended use of the assessment and the information available. For exposure-level decisions, proxies may be used where asset and counterparty-specific information is unavailable, provided that the resulting assessment remains sufficiently specific to the counterparty or asset and the decision being supported. This is particularly important where the assessment is used to identify material risk drivers or evaluate potential adaptation, resilience or other risk mitigation measures.

For portfolio-level applications, broader use of proxies may be appropriate where this supports consistent coverage and comparability across exposures. Proxies may also support screening and prioritisation, including identifying areas where more detailed assessment or additional data collection is warranted.

Several general principles can support the appropriate use of proxies across different modelling approaches:

- **Use proxies where the information required for the assessment is unavailable or incomplete.** More granular, counterparty- or asset-specific information should be used where it is available and suitable for the assessment. Proxies become particularly useful where sufficiently granular information cannot be obtained across the required scope, for example where portfolio-level assessments require consistent coverage across large numbers of counterparties, locations, hazards or transmission pathways. They can also support screening and prioritisation by identifying areas where more detailed assessment or additional data collection is warranted.
- **Identify which part of the assessment is being approximated.** Proxy use should be explicit about the element it replaces and the transmission pathway in which it is used. In site-level modelling, for example, a proxy may substitute for hazard information, exposure or location data, or vulnerability information. In other pathways, proxies may substitute for information on dependencies or for relationships used to estimate market or macro-economic impacts. Distinguishing these different uses is important because they affect different parts of the assessment and have different implications for how the resulting estimates should be interpreted.
- **Make frameworks modular and upgradable.** Physical risk data and methodologies are continuing to develop. Model structures should, where possible, allow proxy information to be replaced or refined as better data become available without requiring the overall transmission framework to be redesigned. For example, sector-level water-use information may provide an initial proxy where counterparty-specific water use is unavailable, while allowing counterparty-specific information to be incorporated subsequently.
- **Maintain consistency across modelling components.** Where proxy-based and more granular approaches form part of the same assessment, they should use assumptions that are consistent with the common (prediction of) physical conditions, time horizon and, where relevant, broader economic conditions applied across the modelling components.
- **Ensure transparency and traceability.** The use of proxies, their underlying data sources, mapping logic and material assumptions should be identifiable and reproducible. Relevant data-quality limitations and uncertainty introduced through proxy assumptions should be transparent, particularly where outputs are used for risk-management decisions.

The following chapters provide more detailed guidance on proxy use within the different modelling approaches. Chapter 4 considers proxies within site-level hazard, exposure and vulnerability modelling, while Chapter 5 addresses approximations that may be required for off-site operational, market and macro-economic transmission.

4. GOOD PRACTICES FOR MODELLING: SITE-LEVEL HAZARD IMPACT

4.1. Introduction

This chapter sets out good practices for modelling **site-level physical impacts**. It focuses on the assessment of physical hazards at specific locations, the definition and use of hazard indicators, and the modelling of resulting physical and operational impacts through hazard, exposure and vulnerability. It also considers the use of proxies where information required for a site-level assessment is unavailable or incomplete.

Site-level physical impact modelling forms one component of the wider transmission framework described in Chapter 3. It can be applied to a corporate's own assets and operations, real estate properties, or other specifically identified locations relevant to a physical transmission pathway. Where, for example, the location of a critical supplier or infrastructure asset is known, site-level methods can be used to estimate the physical impact occurring at that location. Additional analysis may then be required to determine how that impact transmits to the counterparty, as discussed in Chapter 5.

4.1.1. Scope and motivation for site-level modelling

Site-level physical impacts are inherently local and may be highly dependent on the characteristics of the assets and activities exposed. In some cases, relatively small changes in hazard intensity can result in substantial changes in impact. Site-level modelling therefore requires sufficiently granular information on the **hazard, exposure and vulnerability** relevant to the location being assessed.

For the purposes of this paper, **mechanism-based modelling is the preferred approach for assessing site-level physical impacts.** Such approaches explicitly model the relevant hazard, exposure and vulnerability and quantify the resulting physical or operational impact. This is important because similar hazard conditions can have very different consequences depending on what is exposed and its vulnerability, and because the resulting assessment can identify the factors through which adaptation and resilience measures may change the impact.

A mechanism-based approach does not require every relationship within the model to be derived from an engineering or physical-process model. Vulnerability relationships may also be derived empirically or from relevant studies. For example, an empirically estimated relationship between heat conditions and workforce productivity can be applied to exposed workers at a specific location to estimate the resulting operational impact. The defining feature is that the assessment maintains an explicit relationship between the physical hazard, the exposed asset or activity, its vulnerability and the resulting physical or operational impact.

Flood provides a relatively well-developed example of this approach. Models exist that provide flood depths for different return periods, for example 1-in-100-year and 1-in-1,000-year levels. These are based on physical processes and may be calibrated using historical information such as river gauge observations. At the location of a specific asset, flood-depth estimates can be combined with damage curves to estimate possible physical damage. Damage curves may be based on records of historical damage [10] and, in some cases, physical modelling of assets [11]. The resulting model therefore establishes an explicit relationship between the physical hazard, the exposed asset and its vulnerability to damage.

The availability and maturity of these relationships varies considerably between hazards and impact types. For drought and water stress, for example, relevant impacts may develop over longer periods and interact with other factors, making the relationship between the physical hazard and site-level operational impact more difficult to isolate empirically. Some approaches therefore make greater use of sectoral dependence information or other proxy elements, while more narrowly scoped empirical approaches are available for particular activities such as power generation [12]. The use of proxies within site-level modelling is discussed further in Section 4.4.

A **site** is understood here as a collection of one or more assets, such as buildings, infrastructure, productive land, vessels or vehicles, used to generate output in the case of corporates, or as a building, unit or estate in the case of real estate. For corporate entities, site-level impacts may include asset damage and disruption to operations, including resulting production losses and increases in production costs. For real estate, impacts may include asset damage and impairment of functionality, habitability and occupant comfort. In each case, these impacts may subsequently translate into financial outcomes through the transmission pathways described in Chapter 3.

Site-level modelling is commonly described as a **bottom-up** approach, reflecting its starting point in physical hazards, assets and their vulnerability. The NGFS, for example, distinguishes bottom-up modelling focused on detailed financial exposure and vulnerability from top-down modelling that starts from the macro-economic assessment of physical risk impacts to an economy [13]. Bottom-up assessment is not necessarily confined to impacts occurring at a counterparty's own sites however: location-specific physical-impact modelling may also be applied to relevant external assets or dependencies where their locations are known. Chapter 5 considers the additional analysis required to determine how impacts occurring at such external locations transmit to the counterparty.

The use of hazard, exposure and vulnerability as the basis for physical risk assessment is well-reflected in existing climate-risk frameworks. The IPCC Special Report on Managing the Risks of Extreme Events and Disasters [14] provides an important foundation for the hazard-exposure-vulnerability framework, which is carried through into the IPCC Sixth Assessment Report [14] [15] ,while IPCC AR6 Working Group I applies the framework to regional physical risk assessment [16].

The EBA Guidelines [6] do not prescribe a specific hazard-exposure-vulnerability modelling framework but emphasise the importance of considering the geographical location of key counterparty assets and physical collateral, quantifying financial impacts arising from climate-related factors and considering vulnerability to environmental hazards under different climate scenarios and transition pathways. Site-level hazard, exposure and vulnerability approaches are also used within the NGFS climate scenarios, particularly for modelling physical impacts from acute hazards [8].

4.1.2. Site-level modelling components

Site-level models have explicit hazard, exposure and vulnerability components. Following the definitions used by the IPCC [3] and in [4], these components describe the physical phenomenon that may cause harm, what is exposed to that phenomenon, and the susceptibility of the exposed asset, activity, population or resource to adverse impacts.

Hazard, as defined in Section 2.1 following the IPCC definition, refers to the potential occurrence of a natural or human-induced physical event that may cause adverse impacts on people, property, infrastructure, livelihoods, services or environmental resources. For site-level modelling, hazards are represented quantitatively through **hazard indicators**. For example, fluvial flood may be represented through flood depth at different return periods, such as a 1-in-100-year flood depth of 0.6 metres at a particular location. Section 4.2 discusses the definition and interpretation of hazard indicators in more detail.

Exposure refers to the presence of people, livelihoods, species or ecosystems, environmental services and resources, infrastructure, or economic, social or cultural assets in places that could be adversely affected [3] [4]. In a site-level model, relevant exposure information may include the location and characteristics of the asset or activity, its economic use, workforce or other information needed to establish what is exposed to the hazard.

Vulnerability is the propensity or predisposition to be adversely affected by the hazard [3] [4]. It encompasses concepts including sensitivity or susceptibility to harm and the capacity to cope and adapt. In site-level modelling, vulnerability models define how one or more hazard indicators, together with relevant characteristics of the exposure, translate into a physical impact.

The interaction between these components is sometimes illustrated as: Risk = Hazard × Exposure × Vulnerability. This can be useful conceptually but should not be interpreted as a literal modelling equation. The relevant quantities may themselves be represented probabilistically, and the form of the relationship between hazard, exposure, vulnerability and impact depends on the physical mechanism being assessed.

Vulnerability models may be based on physical or engineering models, empirical observations or other relevant evidence. For example, an asset-damage function may relate flood depth to expected damage for a particular building type, while an empirically derived heat-stress relationship may relate temperature or heat-stress conditions to changes in labour productivity. In both cases, the vulnerability relationship translates specified hazard conditions and exposure characteristics into an estimate of the resulting impact. As described in Chapter 3, site-level physical impacts broadly take the form of **asset damage or disruption and impairment of function**. For corporates, this may include damage to physical assets and operational impacts affecting production volumes or costs, including impacts on inputs, labour capacity and infrastructure and systems. Asset damage may itself result in operational disruption while an affected asset is repaired or restored. For real estate, impacts include asset damage as well as impairment of functionality, habitability or occupant comfort.

Adaptation and resilience measures can alter these relationships by changing the exposure or vulnerability of an asset or activity and therefore the resulting physical impact. Financial risk-transfer mechanisms such as insurance are treated separately because they principally affect the financial consequences of the physical impact rather than the underlying physical impact itself.

Where sufficiently granular hazard, exposure or vulnerability information is unavailable, specific components of the site-level assessment may be approximated using proxies. Section 4.4 considers the use of proxies for hazard, exposure and vulnerability information in more detail.

4.1.3. From physical impacts to financial quantification

As described in Chapter 3, site-level physical impacts need to be translated into quantities that can subsequently be linked to financial outcomes. For corporate entities, this means that site-level vulnerability models should generally seek to quantify **asset damage, production loss and changes in production costs.**

Asset-damage vulnerability curves typically relate hazard indicator values to physical damage, for example as a fraction of the **Total Insurable Value (TIV)** of the asset or, similarly, its rebuild cost. Downtime vulnerability curves may relate hazard conditions or asset damage to expected downtime, from which the resulting production loss can be estimated based on the production attributable to the affected site.

Other operational impacts require different vulnerability relationships. For example, a reduction in labour productivity due to heat may result directly in lower production or may be compensated through additional labour or other measures, increasing unit production costs.

For corporate entities, relevant outputs of site-level vulnerability models may thus include:

- **damage:**
  - asset damage, expressed as a fraction of TIV or rebuild cost;
  - production loss arising from downtime while the asset is repaired or restored; expressed as a fraction of the production attributable to the affected site.
- **disruption:**
  - production loss, expressed as a fraction of the production attributable to the affected site[2];
  - increases in unit production costs.

These outputs provide the link between site-level physical impacts and the effects on revenues, operating expenditure, capital expenditure, cash flow and other financial outcomes described in the corporate transmission framework in Section 3.1. The following sections therefore focus on modelling physical damage and operational disruption in forms that can subsequently support financial quantification.

For real estate, site-level modelling similarly needs to consider both **asset damage and impairment of functionality, habitability and occupant comfort**, including anticipated as well as realised impacts. Asset damage can again be expressed as a fraction of TIV or rebuild cost and may also provide information on loss of use or downtime. Other impacts on functionality, habitability and occupant comfort may require different vulnerability relationships or, where sufficiently granular information is unavailable, proxy elements or approximations. These impacts can subsequently be linked to repair and adaptation expenditure, property income, asset value and borrower financial position through the real-estate transmission framework in Section 3.2.

[2] Alternatively, revenue loss may be expressed as a fraction of the revenue attributable to the affected site. Production is used here because revenue also depends on sales price.

4.2. Hazard indicator definitions

Section 2.1 identifies the physical hazards considered in this paper and distinguishes between the definition of a hazard and the indicators used to represent it quantitatively for modelling purposes. This section focuses on the latter. **Hazard indicators are measurable quantities used to represent relevant characteristics of a hazard** and provide the hazard input to the site-level hazard, exposure and vulnerability framework described in Section 4.1: vulnerability models are typically functions of hazard indicators and exposure-related parameters

The appropriate indicator depends on both the hazard and the physical impact being modelled. Relevant characteristics may include the **intensity, probability or frequency of occurrence, duration, spatial extent, or time for which a specified threshold is exceeded.** Different indicators may therefore be appropriate for the same hazard depending on the relevant impact and vulnerability relationship. The tables below provide illustrative indicators for the climate-related hazard categories introduced in Section 2.1.

The indicators and thresholds presented in the tables are **illustrative rather than prescriptive**. Climatic conditions and relevant impact thresholds differ across regions, activities and assets. Individual institutions or data providers may therefore use different indicators, thresholds or calibrations according to their methodology, geographical scope and intended application.

The tables also assign an **indicative priority (1–3)** to each hazard to guide the focus of the modelling discussion in this chapter:

- **Priority 1 – higher indicative priority:** hazards considered more likely to warrant quantitative assessment across a broad range of relevant exposures or activities;
- **Priority 2 – intermediate indicative priority:** hazards that may be material for particular exposures, activities or geographic settings; and
- **Priority 3 – lower indicative priority:** hazards expected to be less commonly material for the corporate and real-estate exposures that are the main focus of this paper, or for which quantitative modelling is less commonly applied.

These priorities are **not assessments of materiality for an individual entity, asset or portfolio**. As described in Section 3.4.1, the hazards selected for assessment should reflect the entity or asset being assessed, its relevant locations and dependencies, and the physical transmission pathways through which the hazard could result in material impacts. A lower indicative priority therefore does not imply that a hazard can be disregarded where it is relevant to the exposure being assessed. **Data availability and modelling maturity affect how a relevant hazard can be assessed and should be considered separately from whether the hazard is relevant in the first place.**

Hazard indicators can be expressed as absolute quantities referring to specified conditions or periods, or as changes in those quantities between different periods or conditions. For succinctness, the tables generally present **absolute quantities.**

The tables consider hazards individually and do not capture **compound hazards or interactions between hazards that may amplify impacts**. Spatial and temporal relationships between hazards, including the representation of coherent physical events, require additional consideration beyond the individual hazard indicators presented here.

Before introducing the hazard-specific indicators, the below sets out several important considerations for interpreting hazard indicators and hazard maps.

4.2.1. Hazard indicators, hazard maps and event sets

Hazard indicators quantify the relevant characteristics of a physical hazard. Depending on the hazard and the impact being assessed, an indicator may describe its intensity, frequency or probability of occurrence, duration, or exceedance of a relevant threshold. Hazard maps represent these indicators spatially, showing how relevant hazard conditions vary across locations.

The indicator should be appropriate to the physical impact being modelled. There is therefore not necessarily a single indicator for each hazard. For example, flood damage may be related to water depth at different return periods, while heat-related impacts on labour productivity require indicators that represent relevant heat-stress conditions. The following tables provide illustrative indicators for each hazard family.

Two distinctions are particularly important when interpreting hazard indicators and maps, especially acute.

A hazard indicator characterises the set of possible outcomes; it does not predict what will actually occur. A common case is that hazard indicators specify the probability distribution of outcomes. For example, a 1-in-100 year flood depth is the depth for which the exceedance probability is 1%[3]. A set of flood depths for different return periods defines an exceedance probability distribution.

A hazard map should not be interpreted as the footprint of a physically plausible single event and in fact does not provide information about event footprints at all. A probabilistic flood map, for example, provides the annual probability of occurrence of flood events of a certain depth at every location, but an actual flood has a spatially coherent footprint determined by hydrology and topography. This distinction matters where simultaneous impacts across several locations need to be assessed: location-based hazard maps can identify where exposures experience a peril, but do not show which locations would be affected together in a particular event. **Event sets** are commonly used to model the latter[4]. Approaches that represent a range of possible events and their spatial footprints under consistent climate conditions are identified as an area for further methodological development in Chapter 7.

Hazard conditions also change over time. Current-climate hazard models are commonly informed by historical observations and modelling of the relevant physical processes, while future estimates may be conditioned on climate projections such as CMIP or CORDEX [17] [18]. Climate change can alter the distribution of possible hazard outcomes, including their frequency and severity. A hazard level associated with a given probability under current climate conditions therefore need not correspond to the same physical intensity under future climate conditions.

Future hazard maps are often keyed by **climate scenario, time horizon and underlying modelling assumptions.** Climate futures are commonly specified either by global warming level, i.e. the rise in global mean surface temperature relative to pre-industrial (e.g. 2, 3, 4 °C) or by emissions scenario, named after nominal radiative forcing in 2100 (the 8.5 W·m-2 of RCP8.5, or SSP5-8.5 in CMIP6, which pairs the forcing to a socio-economic pathway). The underling modelling assumptions include the choice of climate model or models used from the CMIP/CORDEX ensembles.

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[3] Either exactly or approximately depending on the convention used to define the return period and whether Bernoulli or Poisson processes are used to model occurrence.

[4] Modellers with a quantitative finance background may find it helpful to think of hazard maps as defining the marginal probability distributions and the event set as supplying the dependence structure (copula).

Climate change introduces deep uncertainty because the future distribution of possible hazard outcomes cannot be known precisely. Even for a specified emissions or warming pathway, there remains substantial uncertainty around the resulting climate response and how this translates into regional and local hazard conditions. Climate models can provide information on the direction and possible range of change but generally do not provide a precisely known future probability distribution for local physical hazards [19][5] . A future return-period value, such as the flood depth associated with a 1% annual exceedance probability, should therefore be understood as a modelled estimate conditional on the climate and modelling assumptions applied, rather than as a precisely known future hazard level. This does not change the distinction between hazard conditions and individual events: even under a specified future climate condition, many different physical events remain possible.

The **spatial resolution** of hazard information is also important. Physical hazards operate at different spatial scales, and some vary substantially over short distances. The appropriate resolution therefore depends on both the characteristics of the hazard and the exposure being assessed. Hazard information should be sufficiently granular to represent the physical conditions relevant to the location and impact being modelled; the hazard-specific sections below discuss relevant spatial considerations in more detail.

Finally, hazard indicators and maps describe the **hazard component** of physical risk. The resulting physical impact additionally depends on exposure and vulnerability, as described in Section 4.1.

Against these considerations, the following sections set out illustrative hazard indicators for each of the four climate-related hazard families introduced in Section 2.1.

4.2.2. Temperature-related hazards

The table below provides illustrative indicators for the temperature-related hazards identified in Section 2.1. Several of these hazards are closely related, and the appropriate indicator depends on the particular physical impact being assessed. For example, temperature-related impacts may arise through sustained changes in temperature conditions, heat stress affecting labour or other exposed systems, or periods of extreme heat.

[5] For an accessible, detailed discussion of deep uncertainty in climate prediction see David Stainforth, Predicting Our Climate Future: What We Know, What We Don't Know, and What We Can't Know [19]. Stainforth's work explicitly frames climate as a distribution and climate change as a changing distribution, while highlighting the fundamental difficulties involved in assigning decision-useful probabilities to future climate change.

Table 5: Indicators for temperature-related hazards

HAZARD NAME	EXAMPLE HAZARD INDICATOR (highest priority in bold if relevant)	INDICATIVE PRIORITY (1-3)	NOTES
Changing temperature[6]	Mean cooling/heating degree days {above/ below} set of thresholds (e.g. 15.5, 18C or 22C) per year. Days per year with daily average/max dry bulb temperature above set of thresholds* (e.g. **35C** or 40C). Alternatives include daily average temperature with dispersion measures.	1	In practice, also referred to as 'chronic heat'. Typically applied to heating/cooling energy requirement purposes (e.g. heating/cooling degree days), impact on plant machinery.
Heat stress	Days per year with work day mean/daily mean/max wet bulb globe temperature above set of other thresholds (e.g. **32C** or 35C). Similar for heat index / Universal Thermal Climate Index (UTCI).	1	Real estate
Temperature variability	N/A	3	Low likelihood of materiality
Permafrost thawing	N/A	3	May be relevant primarily through resulting ground-instability impacts in susceptible locations.
Heat wave	Number of occurrences per year with at least 3 consecutive days with maximum temperature above set of thresholds in °C (e.g. **25C**, 30C, **35C**).	1	
	[Heat stress/non-survivable heat] Number of occurrences per year with at least 6 consecutive hours of wet-bulb temperature above 35°C.	1	
Cold wave/ frost	Number occurrences per year with at least 3 consecutive days with minimum temperature below set of thresholds in °C (e.g. -10C). Annual number of frost days defined as days with minimum temperature below 0°C.	2	
Wildfire	Probability of occurrence Days per year with Fire Weather Index (FWI) exceeding given threshold (e.g. 15, 21, 38).	1	

4.2.3. Wind-related hazards

The table below provides illustrative indicators for the wind-related hazards identified in **Section 2.1.** Wind hazards may be represented through prevailing or threshold-based wind conditions or, for event-based hazards such as tropical cyclones and storms, through wind intensity at specified return periods.

Table 6: Indicators for wind-related hazards

HAZARD NAME	**EXAMPLE HAZARD INDICATOR** (highest priority in bold if relevant)	**INDICATIVE PRIORITY** (1-3)	**NOTES**
Changing wind patterns	Days per years with mean wind speed above set of thresholds (e.g. 10 m/s). Annual mean wind speed.	3	Changes in wind regimes may be more relevant as inputs to resulting hazards, such as storms or changes in precipitation and drought conditions, than as a standalone site-level hazard.
Tropical cyclone (cyclone/ hurricane/ typhoon)	Sustained (3 sec/1 minute) wind speed for return periods (years), e.g. 10, 20, 50, 100, 200, 1000 years.	1	This indicator captures the *wind component* of tropical cyclones. A tropical-cyclone event may also generate heavy rainfall and coastal or pluvial flooding, which are represented separately under water-related hazards.
Storm	Sustained (3 sec/1 minute) wind speed for return periods (years), e.g. 10, 20, 50, 100, 200, 1000 years.	2	Includes extratropical storms, severe convective storms, blizzards, and sand and dust storms. These storm types have different physical characteristics and may require different hazard indicators; wind speed alone may not adequately represent all relevant impacts.
Tornado	N/A	3	No / limited data availability.

4.2.4. Water-related hazards

The table below provides illustrative indicators for the water-related hazards identified in Section 2.1. The range of indicators reflects the diversity of physical phenomena within this hazard family, including water availability and quality, drought and precipitation conditions, sea-level change and probabilistic flood hazards. Several of these hazards are related but represent distinct physical conditions and should therefore be interpreted according to the specific impact and transmission pathway being assessed.

Table 7: Indicators for water-related hazards

HAZARD NAME	EXAMPLE HAZARD INDICATOR (highest priority in bold if relevant)	INDICATIVE PRIORITY (1-3)	NOTES
Changing precipitation patterns	Total annual precipitation (mm); days with precipitation above set of thresholds (e.g. 1 mm, 10 mm).	3	*Changing precipitation patterns are generally used as inputs to the assessment of resulting hazards*, such as drought, water stress, heavy rainfall and pluvial flooding, rather than as a standalone site-level impact.
Ocean acidification	N/A	3	Primarily relevant as a change in environmental conditions that can affect marine and biological systems; direct site-level modelling approaches are less established.
Saline intrusion	N/A	3	Relevant primarily where assets or activities depend on freshwater resources or are exposed to salinisation of water or soils. Appropriate indicators may relate to salinity levels or the extent of saline intrusion and are likely to be location- and pathway-specific.
Sea level rise	Sea level rise since baseline period (in mm).	2	*Sea-level rise is an important input to forward-looking coastal-flood assessment* and may also contribute to progressive or recurrent coastal inundation.
Water stress	Water basin integrated water demand divided by water supply (unitless).	1	Basin-level indicator of structural pressure on water availability. Materiality depends on the entity's dependence on water and its connection to the relevant water resource system.

HAZARD NAME	EXAMPLE HAZARD INDICATOR (highest priority in bold if relevant)	INDICATIVE PRIORITY (1-3)	NOTES
Drought	Examples broadly comprise the ETCCDI indicators **[20]**, for example Consecutive Dry Days, and drought indicators of **[21]**. An example of the latter: consecutive months per year with SPEI (standardized precipitation minus evaporation index) (or similar index) below set of thresholds (e.g. -2, -3, -3.5).	1	Drought may be represented through indicators of *intensity, duration and frequency,* depending on the physical impact being assessed. It should be distinguished from water stress, which describes a structural imbalance between water demand and available supply.
Heavy precipitation	Annual maximum of daily (24-hr) water-equivalent precipitation (mm).	2	Heavy precipitation may provide a proxy for pluvial-flood hazard where dedicated inundation modelling is unavailable; precipitation intensity alone does not represent resulting inundation.
	Probability of occurrence of large (> 5 cm) hail.	1	Relevance is asset-specific; exposed assets such as solar installations may be particularly vulnerable to hail damage.
Flood (coastal, fluvial, pluvial, ground water)	Flood depth, protected and unprotected, (metres) for return periods (years), e.g. 10, 20, 50, 100, 200, 1000 years.	1	Public-domain data for pluvial and groundwater flooding may be limited, and commercial data may therefore be required. Pluvial flooding is not confined to riparian/coastal area and flood velocity may also be a damage driver.
Glacial lake outburst	Probability of occurrence.	3	No/limited data availability.

4.2.5. Solid-mass-related hazards

The table below provides illustrative indicators for the solid-mass-related hazards identified in Section 2.1. For several of these hazards, quantitative probability information remains limited and susceptibility-based information may therefore also provide a relevant basis for assessment.

Table 8: Indicators for solid-mass-related hazards

HAZARD NAME	EXAMPLE HAZARD INDICATOR (highest priority in bold if relevant)	PRIORITY (1-3)	NOTES
Coastal erosion	Probability of occurrence,	3	Limited data availability, although some datasets based on historical changes in coastline. Coastal erosion is distinct from coastal flooding, although the two may interact and affect the same exposed assets.
Soil degradation	N/A	3	Particularly relevant to land- and biological-production activities; direct site-level asset-damage modelling is less established.
Soil erosion and solifluction	N/A	3	Soil erosion and solifluction arise through different physical processes and may require different indicators; relevance is strongly dependent on land use, terrain and location.
Avalanche	N/A	2	Highly geographically constrained; relevance depends on the location of exposed assets and activities.
Landslide	Probability of occurrence.	1	For the climate-related taxonomy used here, the focus is on *precipitation-induced landslide*; other triggers, including seismic processes, fall outside this climate-focused assessment.
Subsidence	Probability of occurrence. Susceptibility score (e.g. low, medium, high).	1	Covers several ground-instability mechanisms, including differential settlement, *paalrot* ('pile rot') and shrink-swell effects. Tectonic subsidence is conceptually distinct from these climate-related mechanisms.

4.3. Hazard and vulnerability modelling good practices

The following sections build on the hazard indicators defined in Section 4.2 and set out suggested good practices for **hazard and vulnerability modelling**. The approaches are illustrative rather than exhaustive, and exclusion does not imply that a model is unsuitable. The discussion focuses primarily on hazards and physical impacts for which participating institutions have identified sufficiently developed modelling approaches and resources. Depending on the entity and transmission pathway being assessed, relevant impacts may include asset damage and related downtime, as well as impacts on inputs, labour capacity, infrastructure and systems, functionality or habitability. Where sufficiently granular information or modelling relationships are unavailable, the proxy approaches discussed in Section 3.4.4 may be applied.

4.3.1. General principles

Hazard and vulnerability models should in general have the following properties:

Appropriate spatial granularity: Hazard exposure should be modelled at a spatial resolution appropriate to the asset, activity or resource being assessed and to the spatial scale over which the hazard varies materially.

Ability to quantify physical and operational impacts: The model should produce impact measures that can be translated into financial outcomes and, where required, incorporated into existing banking risk models and frameworks.

Forward-looking: Ability to assess physical and operational impacts under current and projected future climates.

Ability to incorporate adaptation and resilience measures[6]**:** for example regions protected against riverine or coastal inundation; features of assets providing resilience.

Ability to represent different temporal manifestations of physical hazards: modelling should be capable of representing both persistent or gradually changing conditions and discrete or extreme events where relevant to the impact being assessed.

Ability to represent spatial and temporal dependence where material: this may be important where multiple assets or activities can be affected by the same physical event, or where compound hazards can amplify impacts. As discussed in Section 4.2.1, location-specific hazard maps do not by themselves represent spatially coherent events.

[6] Financial risk transfer such as insurance or state support is typically applied to the resulting financial impact produced by the vulnerability model, while adaption may modify exposure or vulnerability within the physical impact model itself.

Resources and public domain/commercial data sets

Copernicus Climate Change Service, and similar services, provide a rich set of public-domain resources for hazard indicator and vulnerability modelling. However, only a subset of these datasets is directly applicable to physical risk modelling of financial institutions. Resources that help financial institutions identify and apply relevant datasets are therefore particularly relevant. The ECB paper [22] and RAIN project [23] [24] are two useful resources. In the individual sections that follow, hazard-specific references to resources are given. These sections are not intended to be a general literature review, but rather select the papers from which participants have directly built hazard or vulnerability modelling approaches.

Various open-source code projects provide resources to facilitate making data sets actionable, notably CLIMADA Open Source[7] [25] and OS-Climate[8] [26] [27]. The libraries serve slightly different purposes, in that CLIMADA has more of an economic modelling focus whereas OS-Climate is a co-operative, and part of the Linux Foundation's FINOS, that provides building blocks to facilitate insertion of physical risk hazard and vulnerability data into financial institutions' internal models.

Open-access regional and national datasets are also available in many jurisdictions through meteorological agencies, geological surveys and environmental authorities. These resources often provide higher-resolution or more locally calibrated hazard information than global datasets, although these can be methodologically disparate. Some participating banks combine regional and global data sets, noting also the importance of consistency with publicly available data, but also the technical challenge that this presents.

The following sections provide suggested modelling approaches and public-domain resources, but do not list commercial vendors. The resources are split into:

- hazard indicator models and
- vulnerability models.

The intent is to define good modelling practices and an emphasis is placed on public domain data, especially those subject to peer review. Commercial data sets have an important part to play, however. This is especially the case where, even if public-domain and open-source building blocks are available, hazard indicator data sets require a significant curation overhead and technical expertise. Riverine and pluvial flood are notable examples for which specialist vendors maintain global models. These can be established catastrophe model vendors, serving the (re)insurance industry; such 'traditional' flood specialists include Fathom and JBA Risk Management. Traditional full-suite cat modelling vendors include KatRisk, KCC, Moody's RMS and Verisk. There are also newer generalists established specifically to serve physical climate risk such as ClimateX, First Street, Jupiter Intelligence and MSCI. These examples are illustrative, not exhaustive. A review of commercial vendors is beyond the scope of this document, but others (e.g. UNEP FI) maintain vendor lists.

In the catastrophe modelling space, Oasis Loss Modelling Framework [28] is a notable open-source platform that provides a standardised calculation engine and data formats; the hazard and vulnerability models it runs may be commercial (licensed from vendors), open, or developed in-house.

[7] CLIMADA Technologies is a separate generalist commercial vendor built on top of CLIMADA.

[8] One of the report authors is an OS-Climate contributor, as a point of disclosure.

Different institutions maintain different approaches to use of commercial data:

- using only public-domain data and/or in-house models;
- using public domain data where possible, but enhancing with commercial data (often for inundation in particular);
- working entirely with third party providers, in particular generalist providers such as Jupiter Intelligence, ClimateX.

Catastrophe modelling disconnect and convergence

Participating banks have noted a convergence between models provided by physical risk third party vendors and those of established catastrophe (cat) model vendors. For example, certain commercial physical risk platforms have moved to embed cat model data, especially for hazards requiring highly domain-specific expertise (e.g. flood) and some participating banks work directly with catastrophe model vendors. Arguably this is unsurprising given that physical risk and insurance hazard models are the same and it is perhaps more surprising that the disconnect existed in the first place; catastrophe models are an important subset of physical climate risk models. The trend is driven by the need for higher resolution and higher quality models and more focus on capture spatial dependence, e.g. through use of event sets.

4.3.2. Temperature-related Hazards

CHANGING TEMPERATURE

Summary

The distinction between the physical impacts and hazard indicators considered under 'changing temperature' and 'heat stress' is not always clear-cut. The following provides illustrative impact channels and possible hazard indicators for vulnerability modelling.

1. *Infrastructure and systems disruption:* days per year with average/max near surface air/water temperature above threshold, combined with thresholds associated with likely levels at which production activities are restricted e.g. regulatory constraints related to waste heat from industrial processes.
2. *Production costs change from heating/cooling needs*[9] : mean annual cooling/heating degree days, used to infer heating / cooling requirements and thereby additional costs.

As noted in 4.1, hazard indicators can be defined as absolute quantities that refer to a specific scenario or year or as the change in quantities for a particular scenario across a particular time span. We continue to specify absolute quantities but note that the representations are equivalent. Moreover, in the case of chronic hazards, it is likely to be the change in, e.g. production or heating/ cooling needs that is relevant under the assumption that current-climate values are taken into account in company financials.

Hazard modelling

In contrast to other hazards, modelling economic loss related to changing temperature, heat stress and heat wave requires various types of hazard indicator, some examples of which are given above. Hazard indicators are often statistical quantities derived from downscaled and bias-corrected climate projection data (e.g. CMIP6/CORDEX [17] [18]).

'Downscaling' can mean *statistical* downscaling or *dynamical*. 'Dynamical' is the running of a higher-resolution regional climate model and generally provides the more realistic representation of local climate processes and extremes. Statistical downscaling typically applies fitted high resolution to lower resolution projections. Statistical downscaling and bias-correction is often based on re-analysis data (e.g. ERA5 [29]). Approaches to downscale to high resolution based on machine-learning (ML) are used in some commercial models, trading off the potential need for higher resolution (e.g. resolving urban heat island effects) against the added complexity of ML-based approaches.

Although dynamically downscaled data sets are generally the better-suited to hazard assessments, practitioners may prefer statistical for better cross-region comparability and global coverage.

[9] This is a cost associated with avoidance of labour capacity impairment / infrastructure and systems disruption.

Spatial resolution

Spatial resolution of ~25 km is quite typical. These hazards generally vary on a coarse spatial scale and the spatial resolution is derived from statistical downscaling of climate projections using ERA5 0.25° data[10]. ERA5-Land 0.1° data can be used to improve resolution to <~ 10 km. ML-approaches may reduce the resolution still further, with potential to capture urban heat island effects or improve resolution where changes in elevation are significant. The CHELSA public domain data sets such as [30], applied to CMIP6 data via [31] represent a 'quasi-mechanistic' alternative to ML for downscaling to kilometre scale. A strong rationale however remains for resolution based on resolution of re-analysis data sets.

Hazards modelling resources

Open-source software libraries exist for bias-correcting and downscaling climate projection data sets such as CMIP6. Examples include *xclim* [32] and *Ibicus* [33]. However, processes can be heavy and public domain sources of pre-downscaled data exist, notably:

- NASA Earth Exchange (NEX) [34] global daily downscaled projections based on CMIP6 [17] data
- Climate Impact Labs [35] [36]

Such data sets can be combined with hazard indicator libraries (*xclim* also provides such functionality for example).

Some data require more physics-based modelling approaches. For example, projections of changes in water stream temperatures [37].

Vulnerability modelling resources

Note that loss of labour productivity is covered separately as part of the following section on heat stress. Modelling impact of temperature on infrastructure and production is in general more challenging. Domain-specific resources include [12] for power generating assets; the authors introduce a framework that can be generalised to other types of assets. For quantifying heating/cooling costs: [38] contains some useful information.

Research exists that estimates the macro-economic impact of heat, such as [39]. Such aggregate relationships may provide useful contextual or benchmarking evidence but are more appropriately treated as macro-economic modelling approaches, as discussed in Chapter 5, rather than as site-level vulnerability models.

[10] 0.25° at the equator corresponds to approximately 28 km at the equator, reducing away from the equator. This resolution can therefore reasonably be described as '25 km' or '30 km', although the pixel size is still smaller across Europe.

Summary

For heat stress, a primary impact channel is *labour capacity impairment* which may be modelled with days per year with workday/daily mean/max wet bulb globe temperature (WBGT) above thresholds, combined with curve(s) relating productivity loss to ambient WBGT.

The resulting operational impact may take the form of reduced labour capacity or increased production costs, for example where additional staffing is used to limit worker exposure or compensate for reduced productivity.

[40] describes a comprehensive list of heat stress indicators, although quantitative vulnerability modelling approaches have only been suggested for a subset of these.
Hazard modelling

See section for 'Changing Temperature' above; the same principles apply.

It is noted that indicators based on sub-daily resolution (e.g. 6 consecutive hours) are likely to be based on approximations to climate models data, e.g. 4 + 4 + 4 models [41] which assume a certain number of working hours at daily maximum, daily mean and the average of the two.

Spatial resolution

See section for 'Changing Temperature' above.

Hazards modelling resources

See section for 'Changing Temperature' above; suitable hazard indicators can be inferred from down-scaled, bias-corrected CMIP6 data for example.

Vulnerability modelling resources

Impact on labour costs can be quantified using information from papers such as the International Labour Organization [41] and [42]. A useful review is [43].

Parts of the literature also estimate heat-related labour impacts at broader sectoral or macro-economic levels (e.g. [44]). These approaches are discussed conceptually under the wider modelling framework in Chapter 5.

Summary

Two relevant impact channels with possible hazard indicators for vulnerability modelling are the following

1. *Infrastructure and systems disruption during heat wave conditions:* number of occurrences per year with at least 3 consecutive days with maximum temperature above set of thresholds, combined with curve relating this to restriction in production activities.
2. *Loss of production from impact on labour during extreme heat:* number of occurrences per year with at least 6 consecutive hours of wet-bulb temperature above 35 °C.

Hazard modelling

See section for 'Changing Temperature' above.

Spatial resolution

See section for 'Changing Temperature' above.

Hazards modelling resources

See section for 'Changing Temperature' above. (Bias-corrected/downscaled) daily projections are a suitable starting point, although focus on statistical models is on lower probability/higher severity events. There is a stronger rationale for use of downscaling techniques, for example to model urban heat island effects.

Vulnerability modelling resources

See section for 'Changing Temperature' above.

Summary

The focus is primarily on asset damage and related downtime, although other operational impacts may also be relevant in certain cases[11].

Approaches include the modelling of the following:

- Annual probability of occurrence, combined with damage given occurrence (as fraction of total insurable value, TIV). Damage given occurrence may be a function of asset characteristics (e.g. construction standards relevant to resilience to ignition by embers). Datasets for inferring asset damage are limited and assumption of total loss is likely to be a reasonable approach.
- Days per year with Fire Weather Index (FWI) exceeding given threshold (e.g. 15, 21, 38) combined with damage given occurrence.

Hazard modelling

Hazard indicators based on probability of occurrence of wildfire are probably the most convenient in order to model economic loss, although indicators such as the Fire Weather Index are also appropriate, if the link to damage/disruption can be made.

Hazard models should ideally take account of factors that contribute to fire occurrence probability:

- meteorological (e.g. via Fire Weather Index or equivalent, which takes account of temperature, relative humidity, wind speed and precipitation);
- features related to fire propagation (such as land-use, biomass indices, slope and elevation);
- features related to fire ignition and suppression (such as proximity to cities).

This can be done through models of probability or by multi-indicator approaches (e.g. use of FWI and biomass indices in combination). Commercial models, and models in the literature, are often based on machine-learning approaches, whereby instances of fires (e.g. inferred via burnt area) are inferred from explanatory variables above. In the public domain ECMWF in particular have developed models along such approaches [45] [46] [47].

Alternative approaches include the simulation of fire events, with the advantage of capturing spatially coherent event footprints. Additional hazards metrics include intensity distributions typically fireline intensity in kW/m. The US Forest Service's FSim-based national dataset [48] is a relevant benchmark. Although no Europe-wide equivalent appears to exist, national maps have been generated based on the underlying approach of [49].

[11] e.g. labour capacity impairment from smoke effects; input impairment in case of agriculture; infrastructure and systems disruptions from damage to transport, electricity and communications infrastructure.

Spatial resolution

Although Fire Weather Index varies on a multi-kilometre-scale, probability of occurrence of fire depends on the characteristics of the terrain, such as slope, presence of biomass, land use/land cover, features which are available on a ~100 m resolution scale or even smaller [50] [51].

Hazards modelling resources

Public domain datasets providing probability of occurrence of wildfire are sparse, but becoming more widely available [46].

Vulnerability modelling resources

A number of studies deal with modelling damage given that an asset has appeared within a burnt area, although much of the work seems to be based on CAL FIRE data [52], from which it is arguably difficult to infer damage across different asset types and regions. Construction guides such as [53] are another route.

4.3.3. Wind-related Hazards

TROPICAL CYCLONE (Cyclone/Hurricane/Typhoon)

Summary

This section relates specifically to wind. Tropical cyclones generate multiple correlated hazards, including extreme wind, heavy precipitation, pluvial flooding and coastal inundation from storm surge. These hazard components should be modelled in a physically consistent manner while avoiding double counting of resulting impacts.

For the wind component, a common approach is to combine sustained or peak wind speed (there are methods for inferring one from the other) at a range of return periods (e.g. 10, 20, 50, 100, 200 and 1,000 years) with vulnerability curves relating wind speed to asset damage.

Hazard modelling

Wind is split into two sub-types which are distinct as regards the level of confidence in predictions of changes under climate scenarios:

- Tropical cyclone
- Extratropical cyclone (e.g. European Winter Storm)

Confidence in projected changes to the frequency and severity of extratropical cyclones remains limited [16], which should be reflected in the interpretation of climate-conditioned estimates.

Hazard indicators comprise peak wind speed for return periods spanning (at a minimum) 1-in-50 years to 1-in-1000 years events. This follows from the need to model economic loss, wind damage curves typically being based on sustained or gust wind speed, and from the need to model rare but severe events.

Spatial resolution

Spatial resolution of <~ 25 km is quite common as wind hazards generally vary over multi-kilometres-scale as do the climate models and reanalysis datasets (e.g. ERA5). Peak gust wind speed however is related to surface roughness and models including such refinements may have sub km resolution, for example [54].

Hazards modelling resources

CMIP6 data is generally not considered useful for generation of tropical cyclone tracks in future climates because of its insufficient resolution, although higher resolution models such as HighResMIP [55] are more successful. Approaches such as that of [56] and [57], which model the underlying physics, are probably more appropriate. In both cases, public domain data sets exist.

Machine learning approaches (see e.g. [58]) are also becoming more common.

Vulnerability modelling resources

Public domain resources include [59], which provides a generic set of vulnerability curves. The US-based FEMA tool includes highly granular vulnerability functions for a range of building types [60]; the documentation also specifies a modelling approach for downtime. The OS-Climate project provides details of how to download and use these curves [26].

Perhaps more suitable for proxy approaches, macro-economic impacts also exist, for example [61].

4.3.4. Water-related Hazards

WATER STRESS

Summary

Water stress impacts may be modelled, for example, using the change in available water for regions of water stress, combined with curves providing loss in production given the decrease in available water. Water stress may also be considered together with drought where temporary climatic water deficits interact with an already constrained water-resource system. The two concepts should nevertheless remain distinct: water stress describes structural pressure on available water resources, while drought describes a climatic water-balance deficit.

Hazard modelling

World Resource Institute Aqueduct [62] is a widely-used source of data related to water stress.

Spatial resolution

The spatial resolution of water stress is, by definition, a hydrological catchment, as water stress quantifies the total availability of water in a basin and the combined withdrawal of water by all users in that basin.

The hydrological models may have approximately 10 km resolution. Different 'levels' of water basins exist (e.g. the HydroSheds levels [63]), but typically level 6 is used in Aqueduct, yielding water basins of ~50-100 km spatial extent.

Hazard modelling resources

A primary resource is the above-mentioned WRI Aqueduct data set. For models including drought measures, indicators may be calculated (for example) from downscaled CMIP6 data using libraries such as *xclim* [32], similar in approach to 4.3.2

Vulnerability modelling resources

Although resources, e.g. [64], exist that describe qualitative dependence on water, and the impact pathways are well-understood, there is a sparsity of applicable cross-sector vulnerability functions; we are not aware of many approaches that quantify without use of proxies. The approach of [12] focussing on power generating assets is one of the few.

Summary

Possible approaches for the modelling of drought impact include:

1. Time-fraction approach: fraction of year for which SPEI, at a given accumulation period, is below a set of thresholds. This may be combined with levels at which production activities may be restricted. This treats drought essentially as a chronic stress.
2. Event-based approach: probability of occurrence of year with a certain number of months with SPEI below threshold; drought as an acute hazard.
3.) Alternative indicators which may be better suited to longer-term drought: similar metrics based on TWSI, PDSI, i.e. those more suited for national comparisons, or indeed any of the indicators of ETCCDI [20].

Hazard modelling

Similarly to hazard indicators used to model temperature-related hazards, drought indicators can be inferred from daily climate projections. See 4.2.2, in particular the section on changing temperature.

A large number of drought indicators are defined in the literature of which many are used in the management of physical risk. These are largely summarised by the ETCCDI indicators [20] and drought indicators of [21]. Approaches that quantify the impact of drought based on such indicators are more sparse, however. Indicators based on SPEI [65] are among the more commonly used, although the standardised nature of this and similar indicators are a point of attention. Models based on such indicators are based on the change in the local frequency/severity of drought; it is the change from current to future climates that is relevant.

Spatial resolution

Spatial resolution of ~25 km is quite common, again driven by ERA5 0.25° data and ERA5-Land 0.1° data.

Hazards modelling resources

See 4.2.2 'Changing Temperature'.

Vulnerability modelling resources

As for water stress, we are aware of relatively few public domain studies that quantify the impact of drought at asset level in a cross-sectoral way. Sector-specific studies exist, especially for agriculture [66] [8], although in such cases drought may be treated in combination with other hazards. Models also exist for power generation [12].

Summary

Modelling approaches include:

1. Probability of occurrence of damaging (differentiated by size) hail combined with probability of damage given occurrence.
2. Probability of occurrence of heavy precipitation combined with probability of damage given precipitation level (e.g. as a result of water ingress).

Heavy precipitation is understood to mean the direct impacts of precipitation; extreme precipitation leading to pluvial or riverine inundation is dealt with in the next section.

Hazard modelling

As for flood, **changes in precipitation** are inferred from CMIP/CORDEX data, although the literature suggests that lower-resolution models may underestimate extreme rainfall. **Hail hazard indicators** are based on a range of methods. An important category are statistical proxy-based methods, for example those using indices such as Significant Hail Parameter (SHIP) or Large Hail Parameter (LHP), or equivalent approaches that model meteorological conditions that can give rise to large hail. These may be calibrated using hailpad or radar-based data to infer probability of occurrence. Models of hail micro-physics are another important category, including the use of hail growth models. Examples of these two categories, especially relevant to European exposures, are AR-CHaMo- ([67], [68]) and HAILCAST-based models [69].

Spatial resolution

See 4.2.2 'Changing Temperature'.

Hazards modelling resources

See 4.2.2 'Changing Temperature' for inference of precipitation data.

The RAIN project provides proxy-based probability of hail datasets [23] [24]. More recent work is based on the AR-CHaMo approach; datasets exist for current climate and have been applied to CMIP6 data [70]. HAILCAST-based data sets are available via the CLIMADA platform [25], see [71].

Vulnerability modelling resources

Heavy precipitation can be used as a qualitative proxy for pluvial inundation, in absence of a dedicated quantitative model.

For hail, a notably helpful resource is [72], which provides damage curves (albeit needing adaption to SHIP, LHP or other indicator).

Summary

A common approach is the modelling of flood depth for a set of return periods (e.g. 10, 20, 50, 100, 200, 1000 years), combined with curves of damage given occurrence of event with a given flood depth.

Hazard modelling

Modelling approaches: should typically include:

1. Hydrological modelling of the occurrence of extreme precipitation under current or future climates, transformed into river discharges (runoff modelling) in riverine case; storm surge modelling in the case of coastal inundation.
2. Hydraulic modelling (aka inundation mapping) of the spread and accumulation of water using appropriate 1D or 2D (depending on region, e.g. river or plain) hydraulic software to model water flow.

Forward-looking coastal-inundation modelling should account for the effect of sea-level rise on the baseline water level against which storm surge occurs. Note that so-called "bathtub" flood models do not model flow at all and are neither 1D nor 2D in that sense. These are generally confined to first-pass coastal inundation models and are less suitable for riverine and pluvial inundation modelling.

Some models of vulnerability consider flow in addition to depth.

Spatial resolution

Resolution is typically <~ 30 metres. Flood risk varies materially on small spatial scales as a result of local topology and flow features; residential assets may also have spatial scales of ~5-10 m.

Hazards modelling resources

'Official' high resolution (<~ 30 metre) local riverine flood models are available for certain jurisdictions, in many cases in response to EU Floods Directive (2007/60/EC), although these may be limited to current climate and may concentrate only most economically important areas.

Notable 'global' public-domain models include the World Resources Institute Aqueduct model [73] (approx. 1 km resolution), models provided by TU Delft (Delft University of Technology) as part of the RAIN data sets [24] (approx. 100 m resolution, pan-European), and models provided by the European Commission Joint Research Centre [74] (approx. 100 m resolution, pan-European, limited to current climate).

Flood hazards are often for 'unprotected' flood depth and are combined with maps that define standard of protection for different regions. Public domain databases of flood protection include [75].

Specialist companies also provide global models for current and future climates. Such models typically comprise hydrological (rainfall/catchment) and hydraulic (flow modelling) components. Even where underlying model components are public-domain, inputs to flood models, especially digital terrain models of sufficient resolution, may be commercial and the cost of curation can be high.

Vulnerability modelling resources

The primary sources of flood damage functions:

- European Commission Joint Research Centre's global flood depth-damage functions [10]. A useful baseline, these are relatively low granularity in terms of asset types.
- The US Federal Emergency Management Agency (FEMA) Hazus tool. Although US-centric these curves are arguably applicable to regions with similar construction standards. On request, the Hazus team have provided sets of damage curves in tabulated form to participating banks who have made this available via [27], providing some details about how to source and utilise. The Hazus damage curves derive mainly from sets provided by the US Army Corps of Engineers [76]. The Hazus documentation also specifies a modelling approach for downtime.
- FLEMO, developed by GFZ Potsdam (Helmholtz Centre for Geosciences) [77]
- Multi-Coloured Manual [78]. Although technically a commercial data set, the resource is prominent and cost-effective enough to include in the list.
- Recent empirical work also provides a basis for modelling business interruption following flooding. Endendijk et al. [79], using post-disaster survey data from the 2021 floods in the Netherlands, estimate depth-duration functions relating flood hazard characteristics to the duration of business interruption. Such functions can complement conventional depth-damage curves by providing a vulnerability relationship between flood intensity and operational disruption, allowing site-level flood models to quantify downtime and resulting production impacts in addition to physical asset damage.

4.3.5. Solid Mass-related Hazards

SUBSIDENCE

Summary

Subsidence may be modelled as an annual probability of occurrence, combined with damage given occurrence (as fraction of total insurable value, TIV). Damage given occurrence may be a function of asset characteristics (e.g. depth of building foundations or historical building stability).

'Subsidence' is taken to mean heat/drought-related subsidence.

Hazard modelling

Shrink-swell subsidence is the risk of occurrence of subsidence resulting from changes in the moisture content of clay-rich soils leading to changes in soil volume. Similar to wildfire, approaches in the literature based on machine learning are increasingly prominent.

Pile rot similarly arises through the interaction of drought conditions and ground characteristics.

Spatial resolution

Spatial resolution should typically be <= 200 m for shrink-swell subsidence to resolve boundaries between local lithologies; soil characteristics vary on a relatively fine spatial scale.

Hazard modelling resources

The RAIN data set [23] [24] contains a number of indicators, albeit including susceptibility scores as opposed to probability of occurrence (see also [22]). Geological datasets at national level can provide complementary information for example France's BRGM susceptibility datasets [80], the methodology of which now incorporates claims data.

Vulnerability modelling resources

Members have noted that country-specific data sets are available from which statistics of incidence of subsidence based on different building characteristics are available. We are, however, not aware of any pan-European approach or review article.

Summary

Landslide may be modelled with annual probability of occurrence, combined with damage given occurrence (as fraction of TIV). 'Landslide' is taken to mean precipitation-induced landslide, consistent with the climate-related scope of this paper.

Hazard modelling

Similar to shrink-swell subsidence and wildfire, statistical approaches in the literature, especially those based on machine learning approaches, are increasingly prominent, both aimed at improved susceptibility and probability of occurrence, e.g. [81]. In Italy in particular, high-quality databases of rainfall-induced landslides are maintained [82], in addition to ISPRA susceptibility datasets [83] [84].

Spatial resolution

Catalogues such as [82] define 'slope-units', which are a natural candidate for unit of spatial resolution.

Hazard modelling resources

The RAIN data set [23] [24] contains a number of indicators, albeit mainly susceptibility scores as opposed to probability of occurrence (see also [22]). For Italy data sets [83] [84] are notable.

Vulnerability modelling resources

Participating banks' approaches concentrate first on susceptibility and probability of occurrence with simple assumptions about damage given occurrence. Refinements beyond this may focus particularly on the type of the landslide; see e.g. [85].

4.4. USE OF PROXIES IN SITE-LEVEL MODELLING

As discussed in Section 3.4.4, proxies may be used where information required for an assessment is unavailable or incomplete. Within site-level modelling, proxies may be used for specific elements of the **hazard, exposure or vulnerability** components of the assessment.

Proxy use can vary considerably in extent. Even relatively granular site-level models commonly rely on some approximations; for example, an individual asset may be assigned to a representative vulnerability class rather than modelled using its precise physical characteristics. The relevant question is therefore which element of the assessment is being approximated and whether the resulting model remains appropriate for its intended use.

The general principles for proxy use are set out in Section 3.4.4. The following sections describe common types of proxy used within site-level modelling and considerations relating to the use of artificial intelligence and machine-learning techniques.

4.4.1. Types of proxy

The following categories describe some common proxy applications within site-level hazard, exposure and vulnerability modelling.

Hazard proxies

Substitute hazard indicators may be used where the preferred hazard indicator is unavailable. For example, an ordinal susceptibility measure may be used in place of an indicator that quantifies the probability and intensity of a hazard. The resulting assessment should be interpreted according to the information contained in the substitute indicator; as discussed in Section 4.2, a susceptibility measure does not provide the same information as a probabilistic hazard estimate.

Exposure proxies

Exposure proxies may be used where sufficiently granular information on the location, characteristics or value of the exposed asset or activity is unavailable.

Location is a fundamental input to site-level modelling and should be obtained at the level of the relevant asset or activity wherever possible. Where precise locations are unavailable, **location proxies may support portfolio-level screening or prioritisation**, for example by assigning activities to representative locations or areas based on sectoral or regional concentrations. Their suitability depends strongly on the spatial characteristics of the hazard. Such approximations may be more informative for hazards that vary over broader spatial scales than for highly location-specific hazards such as flooding. For exposure-level decisions, location proxies should therefore be used with particular caution. Proxies for the location of off-site dependencies, such as critical suppliers, utilities, infrastructure or transport links, are considered in Chapter 5.

Asset archetypes or categories may be used where asset-specific physical characteristics are unavailable, with the asset assigned to a representative class for vulnerability modelling.

Asset-value proxies may be used where asset values are unavailable, for example by estimating value from surface area and an appropriate unit cost. Similarly, production, revenue or other measures

of economic activity may be allocated to individual sites using information such as headcount or production capacity.

Vulnerability proxies

Vulnerability proxies may be used where a vulnerability relationship calibrated specifically to the exposed asset, activity or population is unavailable.

Transferred vulnerability curves involve the application of a calibrated vulnerability relationship outside its original context, for example applying a vulnerability curve developed for one geography to comparable assets in another. The relevance of the original calibration to the new geography, asset characteristics and hazard conditions should therefore be considered.

Empirically derived vulnerability relationships may be drawn from studies of comparable assets, activities or populations. For example, an empirically estimated relationship between heat stress and labour productivity may be applied to an exposed workforce at a particular site. Such relationships can form part of a mechanism-based site-level assessment where they represent the relevant relationship between hazard conditions and the resulting impact.

Sparse empirical calibration may be used where only limited observational evidence is available. This may involve applying an assumed functional form calibrated using a relatively small number of case studies or a synthesis of studies providing partial evidence.

Expert judgement may also be used to inform vulnerability relationships or indices where sufficient empirical evidence is unavailable.

Aggregate or reduced-form modelling should be distinguished from these site-level vulnerability proxies. Where an empirical relationship is used to represent the vulnerability of a specific exposed asset, activity or population, it can form part of a site-level model. Where the model instead estimates an aggregate outcome directly, for example a sectoral, regional or macro-economic impact, it constitutes an aggregate modelling approach rather than a site-level vulnerability proxy. Such approaches are considered further in Chapter 5.

4.4.2. Role of AI

Artificial intelligence (AI) and machine-learning (ML) techniques are increasingly being used to address data and modelling challenges associated with physical risk assessment. They may support the development or enrichment of proxy inputs, although their application is not limited to proxy modelling and may also form part of hazard or vulnerability models.

AI-based approaches should not be viewed as a substitute for robust underlying data. For banking applications, transparency regarding where and how AI is used within the modelling chain remains important. Institutions should be able to identify the modelling steps relying on AI techniques, understand the nature and provenance of the underlying data, and assess the influence of these techniques on the resulting model outputs.

As with other modelling approaches, appropriate governance remains important. Particular attention may be warranted regarding **explainability, reproducibility, auditability, validation against observable data and ongoing performance monitoring.** These considerations are especially relevant in banking applications where model outputs may contribute to risk management, stress testing, disclosure or decision-making processes.

5. CONSIDERATIONS FOR MODELLING: OFF-SITE, MARKET AND MACRO-ECONOMIC TRANSMISSION

5.1. Introduction

Section 3.1 introduced the principal transmission pathways through which physical hazards affect corporate counterparties and translate into financial outcomes. These comprise the asset & operational, market and macro-economic pathways. The asset & operational pathway includes impacts arising both at a company's own operational sites and through dependencies located beyond its operational footprint.

Chapter 4 addressed site-level physical impacts, setting out good practices for assessing how hazards affect assets, activities and resources at specific locations using hazard, exposure and vulnerability-based approaches. These methods can also be applied to a known supplier facility, infrastructure asset or other external location. Additional analysis is then required to determine how an impact occurring at that location transmits to the counterparty.

This chapter addresses the remaining components of the transmission framework. It considers off-site operational transmission arising through dependencies located outside a company's own operational footprint, the market pathway through which physical hazards affect demand, prices and competitive conditions, and the macro-economic pathway through which physical hazards influence the broader economic environment in which counterparties operate.

Off-site operational transmission captures the effects of physical hazards acting on suppliers, infrastructure systems, logistics networks, energy systems and labour markets that support a company's operations. The market pathway captures changes in demand, customer behaviour, competitive dynamics and pricing conditions. The macro-economic pathway captures broader impacts on economic activity, employment, inflation, public finances and financing conditions. Together, these pathways capture sources of financial impact that are not fully explained by site-level assessment alone. A company may experience limited impact at its own facilities yet still face reduced production, higher costs or weaker financial performance through disruption affecting suppliers, infrastructure systems or labour markets, changes in customer demand and market conditions, or effects on the wider economy. Consideration of these pathways is thus necessary to understand the full range of mechanisms through which physical hazards may affect counterparty financial outcomes

This chapter focuses primarily on corporate counterparties. Several of the approaches discussed are also relevant for real estate exposures, particularly where physical hazards affect property demand, rental income, asset values, migration patterns, insurance availability or household borrower repayment capacity. Detailed modelling guidance for governments and financial institutions is outside the scope of this chapter. For financial institutions, many of the approaches described may nevertheless support the assessment of physical risk affecting the counterparties, sectors and assets represented within lending and investment portfolios.

The assessment of these pathways may require different methods, data sources and levels of granularity. As discussed in Section 3.4, the modelling approach should reflect the transmission pathway being assessed and the intended use, while different modelling components used within the same assessment should represent a common and internally consistent physical risk situation. Data on off-site dependencies and the relationships required to model market and macro-economic transmission may also be incomplete, requiring proxies or other approximations. The next section considers these issues before we then discuss off-site operational, market and macro-economic modelling approaches and the interpretation of their outputs together.

5.2. Use of proxies and approximations

Data requirements for modelling off-site operational, market and macro-economic transmission differ from those for site-level modelling. The relevant information may concern **dependencies and relationships between entities, assets, infrastructure, markets and regions**, rather than the characteristics of an individual site. Such information is often incomplete, particularly for supply chains and infrastructure dependencies, and proxies or other approximations may therefore be required.

For **off-site operational transmission**, relevant gaps may include the identity and location of critical suppliers, sourcing regions, infrastructure assets and networks, shared utilities or transport links, as well as information on concentration and substitutability. Where detailed information is unavailable, assessment may focus on critical dependencies and bottlenecks or use broader information on sourcing regions, production concentrations, infrastructure networks or other relevant geographic dependencies. Where the location of a relevant external asset or activity is known, the site-level approaches described in Chapter 4 can be used to assess the physical impact at that location; further analysis is then required to determine how this affects the counterparty.

For **market transmission**, counterparty-specific relationships between physical risk, demand, prices and competitive conditions may not be directly observable. Sectoral, regional or market-level relationships can therefore provide useful approximations where they are appropriate to the level of assessment. The use of an aggregate relationship should remain consistent with the output being estimated; a sector- or market-level relationship does not by itself establish the impact on an individual counterparty.

For **macro-economic transmission**, reduced-form or other aggregate relationships may be used to estimate effects on variables such as output, productivity, inflation or employment. Where the required output is itself regional, sectoral or economy-wide, such relationships constitute modelling approaches at the relevant level rather than proxies for site-level vulnerability. Aggregate macro-economic effects may also provide common background conditions for counterparty or portfolio analysis but should not be mechanically allocated to individual exposures.

Across these applications, the general proxy principles set out in Section 3.4.4 apply: the assessment should be clear about **which information or relationship is being approximated**, the approximation should be appropriate to the intended use, and material limitations should be transparent. Where proxy-based and more granular modelling components are combined, they should also be consistent with the common physical risk situation and assumptions applied across the assessment.

5.3. Off-site operational transmission

Off-site operational transmission represents the extension of the asset & operational pathway beyond the boundaries of a company's own operational sites. As introduced in Section 3.1, operational impacts may arise through inputs, labour and infrastructure & systems. Chapter 4 considered physical impacts at specific locations; this section considers how impacts affecting external dependencies transmit to the counterparty's operations.

Modern production systems depend on a wide range of external inputs, infrastructure networks and labour markets. These dependencies may be located in different regions, countries or continents and may be shared across multiple firms and sectors. As a result, a physical hazard can disrupt operations even where the company's own facilities remain unaffected.

Assessment of off-site operational transmission is often constrained by incomplete information on supply chains, infrastructure dependencies, labour markets and the locations at which relevant dependencies arise. It is generally neither feasible nor necessary to assess every supplier, infrastructure asset or labour pool connected to a business. The assessment should therefore focus on **material dependencies and bottlenecks** whose disruption could have a disproportionate effect on operational performance, including critical inputs, concentrated production regions, infrastructure bottlenecks, logistics hubs, shared systems and critical labour pools.

Where important dependencies can be identified and their locations are known, the hazard, exposure and vulnerability approaches described in Chapter 4 may be used to assess the physical impact at that location. Where relevant information is incomplete, targeted analysis may be combined with the proxy and approximation approaches discussed in Section 5.2.

The following sections discuss three forms of off-site operational transmission corresponding to the operational channels introduced in Section 3.1: inputs transmission, infrastructure & systems transmission and labour transmission.

The objective of the assessment is to estimate operationally meaningful effects that can be translated into company financial outcomes. Depending on the dependency, relevant outputs may include an input shortfall, service outage, delivery delay, increase in input or logistics cost, reduction in workforce availability, or the expected duration of disruption. A general dependency or exposure score does not by itself quantify the resulting effect on operations.

5.3.1. Inputs transmission

Inputs transmission occurs when a physical hazard affects the availability, quality, timing or cost of inputs required for production. It represents the off-site manifestation of the «Inputs» operational channel introduced in Section 3.1.

The 2011 floods in Thailand provide a frequently cited example [86]. Flooding in industrial areas north of Bangkok disrupted global production of hard disk drives and other electronic components, affecting manufacturers and technology companies far beyond the directly affected region. Firms experiencing disruption were often geographically distant from the flood itself, illustrating how physical impacts can propagate through production systems and value chains.

Table 9: Analytical approaches for Inputs transmission

APPROACH	APPLICATION	MAIN LIMITATIONS AND CONSIDERATIONS	ILLUSTRATIVE SOURCES
Critical-dependency assessment	Identifies critical inputs, bottlenecks, sourcing regions and logistics dependencies whose disruption could materially constrain production. Supports assessment of concentration, substitutability, inventories, spare capacity and recovery assumptions.	Relies substantially on company information, sector knowledge and expert judgement. It does not quantify how disruption propagates through the wider economy. Full multi-tier traceability is often unavailable and may be unnecessary where the critical input, production region or bottleneck can be identified directly.	TNFD, *Guidance on value Chains* [87]; UK Government Office for Science, *Global Supply Chains: A Foresight Report on Risk and Resilience* [88]
Targeted geospatial and hazard-impact assessment	Applies hazard, exposure and vulnerability assessment to a known critical supplier facility, sourcing region, processing cluster or logistics node in order to estimate potential operational disruption.	The location and operational importance of the dependency must be known. Hazard exposure alone does not establish the consequence for the counterparty; substitutability, inventories, alternative sourcing and recovery must also be assessed.	TNFD, *Guidance on Value Chains* [87]; UK Government Office for Science, *Global Supply Chains: A Foresight Report on Risk and Resilience* [88]
Input-output and multi-regional input-output analysis	Assesses how a production or capacity shock propagates across sectors, regions and countries through established production and trade relationships.	Standard input-output models assume relatively fixed production relationships and generally represent inventories, supplier substitution, rationing and recovery only to a limited extent. The results describe sectoral propagation and should not be treated as named-company losses.	NGFS Climate Macro-economic Modelling Handbook [89]; Sun et al., "Global supply chains amplify economic costs of future extreme heat risk" [90]
Firm-network analysis	Assesses how disruption propagates through supplier-customer networks and identifies firms, production stages or hubs that create significant cascading effects.	Requires detailed and sufficiently complete multi-tier supplier relationships and information on product specificity. Missing links and limited information on production functions, inventories and substitution materially affect results. Current banking application remains limited.	Inoue and Todo, "Firm-level propagation of shocks through supply-chain networks" [86]

The key modelling challenge is not simply to identify exposed suppliers, but to understand how disruption propagates through production and distribution systems. Important considerations include the criticality of specific inputs, the concentration of production and processing, dependence on transport infrastructure and the ability to substitute suppliers or sourcing regions.

The assessment should start with the critical production dependency rather than an exhaustive supplier map. Mapping adds most value where a particular supplier, production technology, region, water basin, processing stage, port or corridor is difficult to replace. Particular attention should be paid to bottlenecks

and concentration points. The significance of a supply disruption depends on more than the hazard itself. A disruption affecting a highly concentrated production region, a specialised processing stage or a major distribution route may propagate widely through a value chain even where the original physical impact is geographically limited. Geographic diversification, alternative sourcing options and inventory buffers may substantially reduce transmission.

In selected cases, the impacts of physical hazards on critical inputs can be assessed using approaches similar to those described in Chapter 4. For example, a company dependent on cocoa production may assess drought, heat stress or biological hazards in key growing regions. Similar approaches may be applied to agricultural commodities, biological inputs, critical minerals or specialised manufacturing clusters. Such assessments are most relevant where production is highly concentrated, and substitution options are limited.

In many situations, however, input transmission occurs through changes in availability, delivery times or input prices rather than through the complete loss of a specific supplier or location. Detailed information on supply chains is often unavailable and full value-chain traceability may not be feasible. Assessments should therefore focus on understanding the resilience of critical dependencies rather than attempting to map every supplier relationship.

GOOD PRACTICE CONSIDERATIONS

1. **Identify the critical input and the point of dependence.** Determine which input or service is required, where it becomes difficult to substitute, and whether production or processing is concentrated in particular facilities, regions or resource systems. Do not treat supply chain risk as a supplier mapping exercise: understanding how disruption propagates through the system is frequently more informative than knowing the location of every supplier. Detailed supply chain information is often unavailable, particularly beyond the first tier of suppliers. TNFD similarly notes that full value-chain traceability is not always feasible and that dependency-based approaches may be more appropriate in many situations [91].
2. **Assess the potential disruption.** Where relevant locations are known, assess the physical hazard and resulting impact on production capacity, processing, transport or delivery.
3. **Assess resilience and translate the impact.** Consider inventories, alternative specifications, supplier qualification time, spare capacity, contractual access, alternative routes and expected recovery. Translate the result into input availability, delay, procurement cost, production volume and working-capital effects.

5.3.2. Infrastructure and systems transmission

Infrastructure & systems transmission occurs when physical hazards affect the shared systems on which economic activity depends. It represents the off-site manifestation of the «Infrastructure & Systems» operational channel introduced in **Section 3.1.**

Companies depend on a range of systems that sit outside both the operational site and the traditional supplier relationship. These include electricity networks, transport systems, logistics infrastructure, communications networks and water systems. A facility may remain physically undamaged while being unable to operate because electricity is unavailable, a transport corridor is disrupted, telecommunications fail or access to water is interrupted.

A manufacturer dependent on a major export port may be affected by coastal flooding disrupting cargo movements even where production facilities remain unaffected. Similarly, disruption of an electricity substation, transmission network or transport corridor may affect operations through loss of service rather than direct damage to company assets.

Table 10: Analytical approaches for Infrastructure and systems transmission

APPROACH	APPLICATION	MAIN LIMITATIONS AND CONSIDERATIONS	ILLUSTRATIVE SOURCES
Critical-node and network assessment	Identifies infrastructure nodes and network connections whose disruption could interrupt essential services, logistics flows or operational access.	Network importance or centrality does not by itself quantify service disruption or economic impact. Information on actual flows, users, redundancy and backup capacity is needed to establish operational materiality.	UK Government Office for Science, *Global Supply Chains: A Foresight Report on Risk and Resilience* [88]
Targeted hazard and vulnerability assessment	Assesses physical hazard exposure and vulnerability of a known infrastructure asset, corridor or facility in order to estimate potential service disruption.	Exposure or damage at the asset cannot be translated directly into disruption for the counterparty. The assessment must establish how the physical impact affects service delivery, users and dependent operations.	Verschuur et al., “Quantifying climate risks to infrastructure systems” [92]
Infrastructure-flow and reliability modelling	Assesses how infrastructure damage or capacity reduction affects service delivery, rerouting, restoration and operational continuity.	Requires data on network components, flows, service areas, backup arrangements and restoration. Such information may be confidential, incomplete or unavailable across large portfolios. Validation of multi-hazard and interdependent-infrastructure models remains limited.	Verschuur et al., “Quantifying climate risks to infrastructure systems” [92]

The key modelling challenge is to understand how physical hazards affect critical infrastructure systems and how disruption propagates through dependent activities. The significance of disruption depends on both the physical hazard and the resilience of the system. Redundancy, alternative routes, backup capacity and recovery capabilities may all influence outcomes.

For corporate analysis, the required output is the change in service available to the counterparty, rather than the hazard score of the infrastructure asset. A port exposed to coastal flooding becomes relevant once the analysis establishes the resulting capacity restriction, delay, rerouting requirement and recovery time.

As with inputs transmission, infrastructure dependencies may sometimes be assessed using location-specific physical risk analysis. A company heavily dependent on a major port, logistics hub, railway corridor, electricity substation or water asset may experience disruption resulting from physical hazards affecting those locations. In such cases, hazard, exposure and vulnerability-based approaches may be used to estimate the physical impact on the infrastructure asset or system; additional analysis is then required to determine the resulting disruption to the counterparty.

Infrastructure transmission should nevertheless be viewed as a systems problem rather than an asset-mapping exercise. The most important risks frequently arise from dependencies on shared networks, bottlenecks and critical nodes whose disruption affects multiple activities simultaneously.

Identification of hazard exposure at an infrastructure asset is only the first stage of assessment. The relevant operational output is the effect on the service provided to the counterparty, including service availability, outage duration, capacity reduction, rerouting possibilities and restoration time. Where these effects cannot be established, exposure of the infrastructure asset should not be interpreted directly as disruption to the counterparty.

GOOD PRACTICE CONSIDERATIONS

1. **Identify the critical infrastructure systems on which the counterparty depends.** The objective is to understand which shared systems are essential for continued operations. Relevant dependencies may include electricity networks, transport systems, logistics infrastructure, communications networks and water systems. Particular attention should be given to infrastructure bottlenecks, major logistics hubs, transport corridors and other critical nodes whose disruption could affect large parts of the business.
2. **Assess how physical hazards may affect those systems.** This may involve analysing electricity grids, transport corridors, logistics hubs, water systems or communications infrastructure. Where critical infrastructure assets, facilities or corridors can be identified, hazard, exposure and vulnerability-based approaches similar to those described in Chapter 4 may provide useful insight into disruption pathways and operational consequences.
3. **Consider the resilience of those systems alongside the hazard itself.** The significance of infrastructure disruption depends on more than the physical hazard. Relevant factors may include redundancy, alternative routes, emergency capacity, backup systems, recovery times and the ability to reroute activities through other infrastructure networks.

5.3.3. Labour transmission

Labour transmission occurs when physical hazards affect the availability of workers required for continued operations. It represents the off-site manifestation of the «Labour Capacity» operational channel introduced in **Section 3.1.** Labour productivity impacts arising at a company's own operational site are addressed within the site-level transmission framework described in Chapter 4. The focus here is labour availability and labour-market dynamics operating beyond the boundaries of a specific site.

Physical hazards may affect labour availability through injury, illness, displacement, transport disruption and longer-term demographic change. Repeated extreme events, chronic water stress, declining agricultural productivity or worsening heat conditions may influence migration patterns, population distribution and labour-market conditions over time.

In some sectors and regions, access to labour may represent a critical dependency. This is particularly relevant where operations depend on specialised skills, seasonal workers or geographically concentrated labour pools. Physical hazards affecting these populations may impair operational continuity even where production facilities themselves remain unaffected.

Labour transmission may occur over multiple timescales. Extreme events may create short-term disruption through evacuation, transport interruption or temporary displacement. Persistent or progressively changing physical conditions may contribute to gradual population movements and changes in regional attractiveness that affect workforce availability over longer periods.

Quantification at named-counterparty level is particularly challenging because labour availability depends on skill specificity, commuting patterns, housing and public services, workforce mobility, migration policy and the feasibility of remote work or relocation. In the absence of counterparty-specific evidence, labour transmission is therefore better assessed through qualitative materiality analysis or bounded regional and sector scenarios than through a generic labour-availability multiplier.

GOOD PRACTICE CONSIDERATIONS

1. identify the critical labour pool and the mechanism of disruption;
2. distinguish temporary absence and workplace-access disruption from persistent regional labour-supply change;
3. use counterparty-specific evidence or bounded scenarios, avoiding mechanical translation of migration or population changes into firm output.

5.4. Market pathway

The market pathway captures changes in demand, realised prices and relative competitiveness resulting from physical hazards. These effects may arise even where a counterparty experiences limited direct operational disruption.

For corporates, market impacts may arise through changes in demand for products and services, shifts in customer preferences, changes in realised sales prices, or changes in the relative competitiveness of producers, locations and production systems. Examples include increased demand for cooling equipment during periods of extreme heat, changing sourcing decisions following repeated physical disruptions, or price movements resulting from the disruption of production elsewhere.

For real estate, market impacts may arise through changes in property demand, occupancy, rental income, asset values and location attractiveness. Physical hazards may influence the desirability of particular locations through their effects on comfort, habitability, insurability and perceived long-term resilience. These effects may emerge even in the absence of significant realised physical damage.

Market impacts may arise from both observed and anticipated physical hazards. Observed impacts reflect realised events and their consequences for markets, customers and investors. Anticipated impacts arise as market participants adjust their decisions in response to expected future physical risks, adaptation requirements and long-term viability. For example, expectations regarding future flood risk, water scarcity, heat stress or insurability may influence investment decisions, demand, occupancy, sourcing decisions and asset valuations before significant physical impacts occur. Market outcomes may therefore develop gradually and reflect a combination of realised impacts and changing expectations regarding future risk.

Table 11: Analytical approaches for market transmission

APPROACH	APPLICATION	MAIN LIMITATIONS AND CONSIDERATIONS	ILLUSTRATIVE SOURCES
Commodity and partial-equilibrium models	Assesses how production shocks affect supply, demand, inventories, substitution, trade and prices within a commodity or sector.	Results are sensitive to assumptions concerning supply and demand elasticities, inventories, trade relationships and substitution. The analysis is generally limited to a defined commodity or sector.	Schenker and Osberghaus, "International Trade and the Transmission of Temperature Shocks" [93]
Trade models	Assesses how physical shocks alter trade flows, market access, sourcing patterns and trade diversion between countries and regions.	Trade adjustment does not determine the effect on a named company. Firm-level consequences depend on contracts, customer and supplier relationships, product differentiation and the ability to change markets or sourcing arrangements.	Schenker and Osberghaus, "International Trade and the Transmission of Temperature Shocks" [93]
Demand and spatial econometric models	Estimates the effect of weather conditions or physical hazards on observable outcomes such as tourism demand, property transactions, occupancy rates or product demand.	Attribution is difficult because demand and location choices are also influenced by incomes, technology, demographics, policy and other market developments. Historical relationships may not remain stable under future conditions, and results generally cannot be transferred directly to named counterparties.	Rising et al., "The Missing Risks of Climate Change" [94]
Computable general equilibrium models	Represent adjustment across multiple markets through prices, trade, demand and substitution between production inputs and economic factors.	Market-clearing assumptions may smooth short-term shortages, rationing and disorderly adjustment. Outputs are conditional on model structure, elasticities and closure assumptions and should not be treated as forecasts or firm-specific revenue shocks.	World Bank, *The Economic Case for Nature* [95]; NGFS, Climate Macro-economic Modelling Handbook [89]

The appropriate approach depends on the market effect being assessed. Commodity or trade models may be suitable for analysing price, quantity, substitution and trade diversion. Historical demand models may support narrowly defined questions concerning tourism, property transactions or particular products. Broader sector or economy-wide models may capture interactions across markets. Results at sector or market level should not be translated directly into named-counterparty revenue or market share without evidence on the counterparty's customer base, product differentiation, competitive position and ability to adapt.

The distinction between market and macro-economic pathways is not always clear-cut. Changes in economic activity, migration patterns, investment decisions and regional development may influence specific markets while also contributing to broader macro-economic effects. Market pathway assessments should therefore focus on the direct implications for demand, prices, occupancy, market share and competitiveness, while recognising that these effects may interact with wider economic developments.

GOOD PRACTICE CONSIDERATIONS

1. Identify the products, services, properties and markets that are most important to the counterparty's revenues, asset values or profitability. The objective is to understand how physical hazards may affect demand, realised prices and competitive position.
2. Assess how observed and anticipated physical hazards may influence demand and realised prices. Relevant effects may include changes in customer preferences, sourcing decisions, market access, occupancy rates, rental demand, property attractiveness, pricing conditions and the relative competitiveness of locations, producers or production systems. Market responses may arise from realised physical impacts, expectations regarding future risk, or a combination of both.
3. Consider both short-term disruption and longer-term structural change. Extreme events may temporarily affect market conditions, while persistent or progressively changing physical conditions may influence investment decisions, market development, migration patterns and location preferences over longer time horizons.
4. Assess market developments alongside other drivers of change. Demand, prices and competitiveness are also influenced by technological developments, demographic trends, policy measures, transition pathways and broader economic conditions.
5. Distinguish market impacts from physical and operational impacts. Changes in demand, prices, occupancy, market share and competitive position should be assessed separately from asset damage and changes in input availability, infrastructure disruption and operational costs, even where the same physical hazard contributes to both effects.

5.5. Macro-economic pathway

Physical hazards may affect individual assets, companies and supply chains, as well as the broader economic environment in which households, businesses and governments operate. Relevant effects may include changes in economic growth, inflation, employment, public finances, financing conditions, trade and sector activity. The discussion in this section draws primarily on the NGFS Climate Macro-economic Modelling Handbook [89] and ECB analysis of physical risk transmission and macro-economic spillovers [96].

Macro-economic effects may arise from both observed and anticipated physical hazards. Realised physical impacts may affect economic activity through asset damage, operational disruption, supply shortages and recovery costs. Expectations regarding future physical risks, adaptation requirements and resilience investment may also influence investment decisions, consumption patterns, financing conditions and asset values before significant physical impacts are realised. As a result, macro-economic effects may emerge gradually through changing expectations and economic behaviour as well as through the direct consequences of physical hazard events.

Macro-economic modelling may serve two distinct roles. It may provide standalone results for economy-wide, sovereign or portfolio analysis. It may also provide common background variables, such as GDP growth, inflation, employment and financing conditions, for counterparty-level financial analysis. In the latter case, aggregate macro-economic shocks should condition the counterparty assessment rather than be allocated mechanically to individual exposures.

Several modelling approaches can be used to assess these effects, including macro-econometric models, computable general equilibrium models and macro-economic scenario analysis. These approaches differ in structure and assumptions, but all seek to describe how physical hazards influence economic activity, prices, investment, employment and financial conditions at national, regional or sector level.

Table 12: Analytical approaches for macro-economic transmission

APPROACH	APPLICATION	MAIN LIMITATIONS AND CONSIDERATIONS	ILLUSTRATIVE SOURCES
Macro-econometric models	Estimate how physical risk shocks affect aggregate economic variables such as GDP, inflation, employment, trade, fiscal variables and financing conditions using historical relationships and macro-economic equations. Physical impacts may enter through damage estimates, productivity effects, sector shocks or externally modelled disruptions.	Historical relationships may not remain stable under structural climate change or extreme events outside observed experience. Tail risks, interacting shocks and unidentified mechanisms may be incompletely represented.	NGFS, Climate *Macro-economic Modelling Handbook* [89]; Rising et al., "The Missing Risks of Climate Change" [94]
Computable general equilibrium models	Assess economy-wide adjustment to physical risk shocks through changes in prices, trade, demand and substitution between production factors. These models estimate sectoral and economy-wide effects on output, employment, prices and resource allocation.	Equilibrium and representative-agent assumptions may underrepresent shortages, rationing, financial distress and disorderly adjustment. Results depend strongly on elasticity and model-closure assumptions.	World Bank, *The Economic Case for Nature* [95]; NGFS, *Climate Macro-economic Modelling Handbook* [89]
Macro-economic scenario analysis	Develop internally consistent physical risk scenarios with associated economic and financial assumptions. Scenarios may provide common conditions for counterparty, portfolio, ICAAP or sovereign assessments, including paths for GDP growth, inflation, employment and financing conditions.	A scenario is a conditional representation rather than a forecast. Its results depend on the physical impacts, transmission mechanisms and assumptions included. Aggregate shocks should condition exposure-level analysis and should not be allocated mechanically to individual counterparties.	NGFS, *Climate Macro-economic Modelling Handbook* [89]; European Central Bank, The Macro-economic Impact of Physical Climate Risk: Evidence from ECB Climate Stress Testing [96]

For banks, the primary role of macro-economic modelling is to ensure that material physical risks are reflected in economic scenarios and planning assumptions. This may include assumptions regarding GDP growth, inflation, sector performance, employment, credit conditions, public finances and financing conditions. Macro-economic modelling provides an important complement to site-level and off-site operational assessment by capturing broader economic effects that cannot readily be attributed to specific counterparties, assets or operational dependencies.

Macro-economic pathways should be viewed as one component of physical risk transmission rather than as a substitute for transmission analysis. Many macro-economic effects originate from the same physical impacts described elsewhere in this chapter, including asset damage, operational disruption, supply-chain constraints, infrastructure failures, labour-market impacts and changes in demand. Macro-economic models provide a framework for representing how these effects accumulate and propagate through the wider economy.

5.6. Combining transmission pathways

Physical hazards may affect counterparties through multiple transmission pathways simultaneously. The same physical event may generate site-level impacts, off-site operational impacts, market effects and macro-economic effects. Assessment of physical risk therefore often requires consideration of several transmission pathways rather than reliance on a single modelling approach. The table below illustrates how severe drought conditions in Southern Europe may propagate to counterparty financial outcomes through different transmission pathways.

Table 13: Illustrative transmission pathways for a severe drought in Southern Europe

PHYSICAL EVENT	TRANSMISSION PATHWAY	ILLUSTRATIVE CONSEQUENCE
Severe drought in Southern Europe	Asset & operational pathway (site-level)	Reduced water availability at the company's own facilities
	Asset & operational pathway (off-site)	Reduced agricultural production, supply-chain disruption and higher input costs
	Market pathway	Higher commodity prices, changing demand patterns and changes in competitive position
	Macro-economic pathway	Higher inflation, reduced economic growth and sectoral impacts

Different transmission pathways should ideally be translated into a common set of operational and financial drivers before assessing credit impact. Examples include production volume, revenue, input costs, operating expenditure, capital expenditure, working capital requirements, asset values and financing costs. Translating pathway outputs into common financial drivers can improve consistency and reduce the risk of double counting where multiple transmission pathways are assessed simultaneously.

For corporate analysis, the individual pathway outputs should be reconciled through their effects on common operational and financial drivers. Site-level and off-site operational impacts should be reconciled through their combined effects on production and distribution volume, unit costs and disruption duration. Market-pathway effects should then be reflected through demand, realised selling prices and market access. Macro-economic variables may provide common background conditions or standalone portfolio-level results, with explicit identification of supply-chain or infrastructure effects already reflected in the macro-economic model. The resulting impacts can then be translated into revenue, operating costs, capital expenditure, working capital, asset values, financing costs and cash flow before application of the bank's credit-risk methodology.

Different transmission pathways may represent different consequences of the same underlying physical hazard occurrence. They should therefore be interpreted together rather than as independent estimates of risk. For example, disruption of agricultural production may influence input availability through the asset & operational pathway, increase food prices through the market pathway and contribute to inflationary pressures through the macro-economic pathway.

Physical hazards may also occur as compound or cascading events. Compound effects may arise where multiple hazards or stressors interact simultaneously or in close succession, such as drought combined with extreme heat. Cascading events arise where an initial physical impact propagates through operational, market and macro-economic systems. For example, disruption of agricultural production may reduce input availability, affect commodity prices, alter demand conditions and contribute to inflationary pressures. These interactions reinforce the importance of considering transmission pathways together rather than in isolation.

At present, there is no generally accepted methodology for combining all transmission pathways into a single physical risk estimate. Different modelling approaches operate at different levels of aggregation and may capture related consequences of the same physical hazard occurrence. Care is therefore required when interpreting model outputs and combining results from multiple transmission pathways. Transparency regarding the scope of each assessment, the transmission pathways included and the limitations of the underlying modelling approaches is particularly important where multiple models are used to support decision-making.

6. MEASURES FOR RISK MANAGEMENT

Chapters 4 and 5 describe approaches for quantifying physical and operational impacts and their transmission into financial outcomes. This chapter considers how these outputs can be expressed as measures that support banking risk management. Depending on the intended use, relevant measures may be defined at different stages of the transmission chain, from physical and operational impacts to financial impacts and banking-risk measures.

The chapter focuses on approaches discussed by participating institutions, including the use of catastrophe-modelling-derived measures, inherent and residual risk, the treatment of adaptation and financial risk mitigation, and measures relevant to collateral devaluation and deterioration of client financial strength. The approaches are illustrative and should be applied in the context of the intended use and the institution's existing risk-management framework.

6.1. Types of measures

Physical risk can be measured at different stages of the transmission chain, depending on the pathway being assessed and the intended use of the assessment. Three broad layers of quantitative measures can be distinguished:

- **physical and operational impact measures,** such as asset damage, changes in production and distribution volume, unit costs or disruption duration;
- **financial impact measures,** such as effects on revenue, costs, cash flow and asset values; and
- **banking risk measures,** such as collateral devaluation, probability of default, loss given default and expected credit loss.

The appropriate measure depends on the transmission pathway and the decision the assessment is intended to support. In some applications, physical or operational impact measures may be used directly or converted into risk scores. In others, they provide intermediate outputs that are translated into financial impacts and subsequently incorporated into banking risk models.

Scores may therefore provide a useful representation of underlying quantitative information for particular risk-management purposes, but they should remain traceable to the underlying physical, operational or financial measures and to the transmission pathway being assessed. This chapter outlines how measures derived from site-level and off-site operational, market and macro-economic models can be combined and translated into measures for risk management.

Catastrophe modelling outputs are a natural choice for the first layer; asset damage and business interruption are typical cat model outputs and are readily extended to quantities such as impact on production and impact on production costs. Some use-cases may derive scores directly from such quantities; others may derive financial metrics from these and ultimately incorporate into existing risk models to quantify impact on collateral or expected credit loss.

Catastrophe-modelling-derived measures

The result of modelling an asset's vulnerability as a function of hazard indicators is in general, a probability distribution describing the possible impact. This impact might be asset damage or disruption (for corporates: impact on production or on production costs). Common measures for describing the impact in quantitative terms, especially relevant to event-based hazards, include **[97]**:

- Annual Average Loss (AAL): the expected annual loss, often specified as a fraction of asset Total Insurable Value (TIV) in the case of damage.
- Occurrence Exceedance Probability (OEP): the probability that the loss associated with an occurrence of an event exceeds a particular value.
- Annual Exceedance Probability (AEP): the probability that the total loss over all occurrences exceeds a particular value. Alternatively, the same information can be represented as a loss associated with a particular return period. A 1-in-100 year loss of 1 million Euros means that there is a 1% probability that the annual loss will exceed that value.

Impact distributions may be used as intermediate outputs for subsequent financial and banking-risk analysis, while measures such as AAL and return-period-based losses may also be used directly to define risk measures or scores. Both return-period-based losses and AAL metrics may be used to define scores. 100 years is a common choice for return period (in cases where a single period is selected) both in describing impacts and the underlying hazards e.g. flood models may, for example, define areas according to location-specific flood depth associated with a 1% annual exceedance probability[12].

Risk measures and use of scores

Participating banks make use of qualitative but, increasingly, also quantitative, impact-based scores in their risk management frameworks. Quantitative scores may be defined from these underlying measures, AAL or return-period losses, to categorise assets in a portfolio, according to the transmission channel of risk. For example, where the transmission channel is devaluation of collateral, AAL can be used to identify assets for which the risk of devaluation is highest.

Importance of lower return periods

Banks' physical risk modellers are arguably more interested in lower return periods than their insurance counterparts; existing catastrophe models often concentrate on rare but severe events. Lower return periods (say 10-20 years) may however have a greater role in devaluation than in driving insurance losses.

[12] Mathematically, an asset owner has approximately a 1-in-4 chance of experiencing an event more severe than the 1-in-100 year level over an ownership period of 30 years – which may explain why 100 years is a common choice.

6.2. Inherent and residual risk: dealing with uncertainty

A challenge faced by banks is how to deal with highly uncertain elements of physical risk models alongside elements which are more readily modelled. Mitigation is one of the most important of the former:

- the extent to which insurance remains available and affordable across different markets under a future climate and
- how state support evolves

are both highly uncertain, particularly in the long term. To deal with this, some participating banks make use of the concepts of 'inherent risk' and 'residual risk'. In many cases it is feasible to model whether an asset is exposed and vulnerable to climate hazards; for example, the risk to an asset from riverine inundation can be quantified using models of flood depth at different return periods. This is the 'inherent risk'. The portion of the portfolio that has a material inherent risk, and indeed that which does not, is already useful information, for example in defining risk appetite.

In the case of a real estate asset, for example, when considering the likelihood of asset devaluation, the residual risk would take into account mitigation: does the asset fall under a jurisdiction where insurance and cross-subsidisation are both mandated by the state in order to keep insurance available and affordable – and is it likely that this status quo will persist into the future? Assumptions regarding the continuation of such arrangements may therefore be subjective or based on expert judgement. Hence the assumptions are quite different, and it can be useful to state both inherent and residual risk measures so as to separate out deeply uncertain elements.

6.3. Modelling adaptation and financial risk mitigation

Adaptation and financial risk mitigation act at different stages of the physical risk transmission chain and are therefore generally reflected differently in risk models.

Adaptation and resilience measures can modify the exposure or vulnerability of an asset or activity and therefore the resulting physical impact. For example, knowledge of an asset's characteristics (e.g. construction materials and characteristics) may motivate use of an alternative vulnerability curve within some family of curves. Some vulnerability modelling approaches define methods to modify curves depending on parameters, e.g. height of first finished floor for flood **[76]**. Standard of protection is also an important concept, especially in flood modelling.

Flood models may comprise 'unprotected' and 'protected' flood depths, reflecting hazard conditions in the absence or presence of protections such as levees. Standard of protection (SoP) is often expressed in return-period terms; for example, a 100-year SoP indicates protection designed with reference to a 1-in-100-year flood level under the applicable climate conditions. As well as regions, individual assets may also be characterised by their standard of protection, for example power-generating assets subject to particular regulatory standards.

Financial risk mitigation, in contrast, does not generally reduce the underlying physical impact. Insurance or state support may provide a cash flow following a qualifying event that offsets part of the resulting financial loss. Whether an asset is insured or not can be a source of significant (epistemic) uncertainty. For financed assets and collateral assets, financial institutions are more likely to have access to this kind of asset-level information, including insurance. For other assets of corporate counterparties, such information may be more difficult to source.

In the absence of asset-specific insurance data, an alternative approach is to model insurance uptake in a statistical way, for example at a regional/sectoral level. Such information can provide a proxy for insurance coverage where exposure-specific data are unavailable. It may be feasible to source regional/sector-specific values for uptake and, potentially, limits and deductibles [98].

A further option is to complement inherent risk measures with separate indicators of insurance coverage, e.g. the fraction of assets for which insurance cover is available.

6.4. Measures for market-driven collateral devaluation

Where the transmission channel of risk is devaluation of an asset, driven by changes to the market, some participating banks make use of the quantitative inherent risk measures defined above, most commonly either Average Annual Loss (AAL) or 1-in-100 year loss. The inherent AAL/1-in-100 year loss is calculated before insurance is taken into account, but including any known adaptation measures. Both can be used as indicators to identify assets most at risk of future devaluation.

In the case of AAL, the concept of 'actuarially fair' premium is a potentially useful one; assets most at risk of devaluation can be assessed by considering the point at which a fair premium becomes unaffordable. Arguably the 'fair' premium might include capital and risk loading, but this is a more involved topic beyond this document scope. As an example, an AAL of > 1% may be considered the point at which insurance becomes unaffordable; > 0.2% representing the point at which it starts to become unaffordable (see e.g. [99]). Similar arguments can be made for 1-in-100 year loss.

As noted in Section 3.2, devaluation can come from anticipated future damage, reduced functionality or increasing adaptation requirements and is by no means driven solely by risk of increase of an insurance premium. Rather the 'actuarially fair' premium is a mechanism to quantify the impact on asset value. Suggested good practices are then to:

- calculate inherent risk measures based on AAL and/or return-period-based losses;
- assign thresholds at which the risk of devaluation can become material;
- take account of current and future mitigation, for example by modifying thresholds depending on jurisdiction.

Deep uncertainty and expected loss measures

In order to calculate measures such as expected credit loss, it is necessary to model the devaluation of an asset which, as noted above, includes highly uncertain elements. Some participating banks treat exposure-based and portfolio-based use cases differently to scenario-based, noting that uncertain elements (in particular those subject to deep uncertainties) can more readily be integrated in scenario-based calculations.

Risk appetite and Pillar 3 reporting

The approaches above allow for an identification of assets for which risk of devaluation is highest. This comprises both inherent risk, before mitigation is taken into account, and residual, where jurisdiction-specific and subjective elements may be included. Both inherent or residual risk scores are useful for defining risk appetite.

At time of writing, there is no universally accepted definition of a financially 'exposed' asset and definitions can vary significantly, for example in the context of Pillar 3 reporting. This chapter advocates the use of approaches that take account of *vulnerability* of an asset to a climate hazard in an explicit way, noting that those assets most at risk of devaluation may be regarded as the ones that are financially exposed. We would also note the difficulty in any attempt to define 'pure exposure-to-hazard' measures; true hazard-exposure measures are arguably not that useful and most actually include vulnerability but in an *implicit* way[13]. It is arguably more robust to note that vulnerability is required and to make this explicit.

6.5. Measures for deterioration of client financial strength/ creditworthiness

Section 3.1 describes how physical hazards may affect a corporate counterparty through asset & operational, market and macro-economic pathways, while Chapters 4 and 5 discuss approaches for modelling the resulting physical and operational impacts. For risk measurement, these impacts need to be translated into their effects on the counterparty's financial position and, ultimately, financial strength or creditworthiness.

For site-level and off-site operational impacts, relevant financial effects may include:

- expenditure required to repair or replace damaged assets;
- loss of production and associated revenue;
- increases in production and operating costs; and
- additional investment or working-capital requirements arising from disruption or adaptation.

Market and macro-economic pathways may additionally affect revenues, costs, financing conditions and other financial drivers. Where several pathways are material, their effects should be reconciled through the common operational and financial drivers described in Section 5.6 before assessing the resulting change in financial strength.

[13] One could argue that the portion of assets within a 1-in-100 year flood zone is a 'pure exposure-to-hazard' measure. However flood zones may be defined subject to some minimum depth threshold and even if this is zero that includes the tacit assumption that a flood of any depth is damaging. Extending this to wind makes the issue more clear: some threshold is needed to define a region 'exposed to wind' and that threshold is set on the basis of a wind speed that can cause damage.

A general approach is therefore to:

- quantify the relevant physical and operational impacts;
- translate these into counterparty-level cash-flow and financial-statement effects;
- aggregate the resulting effects at entity level, taking account of potential overlap between transmission pathways; and
- assess the resulting change in financial strength or creditworthiness using the relevant financial or credit-risk methodology.

The final risk measure depends on the intended use. For exposure-level applications, measures may be used to identify counterparties for which physical impacts could result in a material deterioration in financial strength and to understand the principal drivers of that deterioration. Portfolio-level applications may aggregate these measures to identify concentrations or compare risk across counterparties, sectors or regions. Scenario and stress-testing applications may combine the resulting financial effects with the applicable credit-risk models to assess portfolio-level consequences under the specified conditions.

Candidate quantitative measures include:

- AAL or losses at specified return periods for asset damage, production loss or cost increases;
- changes in relevant financial metrics or cash flows resulting from the modelled physical impacts; and
- changes in credit-risk measures derived by applying the institution's credit methodology to the resulting financial impacts.

Where scores are used, thresholds may be calibrated to identify levels of physical or financial impact at which deterioration in creditworthiness could become material.

The distinction between **inherent and residual risk** may also be useful for this banking transmission channel. Inherent measures can show the modelled impact before financial mitigation is taken into account, while residual measures incorporate relevant mitigation assumptions. Presenting both can help distinguish the underlying physical risk exposure from the effect of assumptions concerning insurance, state support or other financial mitigation.

7. NEXT STEPS

The C-ESG Risk Round Table has laid important groundwork for developing a common approach to assessing and managing physical risk. However, practices continue to evolve, and practical and methodological challenges remain in assessing and quantifying evolving physical risks. This chapter identifies areas that could be explored further in future work by the Round Table. This document set out to define taxonomies to establish a common language, identify the important transmission channels of risk for banking use cases (Chapter 3) and provide concrete and actionable approaches to risk management, focussing particularly on 'site-level' impacts (Chapter 4), extending this to off-site, market and macro-economic transmission (Chapter 5).

Chapter 4 is non-exhaustive, setting out to describe good modelling practices and provide resources that are used by participating banks; it concentrates on what is readily actionable. As such, next steps may **build on and extend** the approaches set out Chapter 4 as models and practices develop. The authors and contributors welcome feedback from practitioners and modellers therefore, e.g. related to alternative modelling approaches.

Nature risk is notably largely out of scope of this document. The document aimed nevertheless to set the groundwork for the inclusion of nature within a single physical risk framework, proposing modifications for including state of nature and a taxonomy of proxy approaches for site-level modelling particularly relevant for embedding risks with nature component. Perhaps the most obvious next step is the extension to nature-related physical risk.

Event-based approaches are an area likely to evolve further over time. This comprises both the use of catastrophe models and more general scenario analysis approaches, including narrative scenarios representing compound or cascading physical risk situations with several hazards or transmission mechanisms.

Banks may lack sufficiently complete information on counterparties' operating assets and external dependencies, and uncertainty increases where supply-chain, infrastructure, market or other transmission pathways are included. The appropriate level of sophistication and the circumstances in which event-based approaches provide material additional insight therefore remain areas for further practical guidance.

Supply chain risk is also a candidate topic for a subsequent working group. While this document identifies some good practices, it does not yet provide readily actionable approaches.

Two notable data challenges relate to the sourcing of information relevant for physical risk assessment of counterparties' **operating assets** and the current and future state of **insurance**, e.g. statistical uptake and durability data in the absence of asset-specific information. In both cases, the working group would likely add value through defining a common approach and shared set of resources, as opposed to a shared data repository.

This document does not deal with **loss tagging**, i.e. the identification of credit losses, defaults, impairments or operational losses with the occurrence of a physical event. There is scope therefore to collect good practices on historical loss tagging.

Finally, elements specifically related to operational practices around the credit process and provisioning are out of scope of this document. We do not cover, for example whether banks restrict LTVs based on physical risk assessment nor discuss best practices which are specific to IRFS 9. Nor is the calculation of expected credit loss addressed in detail, beyond foundational elements such as noting the role of deep uncertainty. These may also be elements to tackle in subsequent work.

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