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Quantitative assessment of the financial materiality of climate physical risks: a case study

Alessi, L.
Giacomelli, A.

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Executive summary

The notion of risk materiality was introduced to increase transparency for investors. The general principle is that only risks that are not material, i.e. that are negligible, for a given company can be omitted from that company's disclosures. Originally, the concept of materiality only related to financial information. However, with the sustainability discussion becoming increasingly relevant, academics, investors, non-governmental organizations, and policymakers are now paying more attention to information on the environmental, social and governance (ESG) dimensions, for the proper assessment of financial risks.

In the context of sustainability, the discussion on materiality has recently focussed on the concept of **'double materiality'**. This refers to need of considering, for a comprehensive assessment, both **financial materiality** (the 'outside-in' perspective), which examines the impact of sustainability matters (for instance climate change, human rights, or resource depletion) on a company's financial condition and performance, and **impact materiality** (the 'inside-out' perspective), which assesses the impact of a company's activities, products, and services on the environment and the society, and how these impacts can contribute to or hinder sustainable development. In the European Union, the Corporate Sustainability Reporting Directive (CSRD) and the European Sustainability Reporting Standards (ESRS) provide the general principles underpinning the materiality assessment. However, neither the ESRS nor the relevant implementing guidance document indicate any specific methodology for its practical implementation.

This paper offers a **case study, focussing on the quantitative assessment of the financial materiality of climate physical risks**, i.e. those linked to long-term impacts of climate change (such as sea level rise), as well as more frequent and severe natural hazards. Climate physical risks are particularly relevant, as the regulation mandates all firms in the scope of the CSRD, irrespectively of their sector of activity, to provide details on their materiality assessment in relation to climate change. Moreover, a quantitative assessment of the financial materiality of climate physical risks is a necessary step to develop adequate adaptation solutions.

The case study focuses on the establishment of a farm on an island located in the Venice lagoon. Financial materiality is assessed with respect to both long-term risks (chronic risks), in particular sea level and temperature rise, and climate-related natural disasters (acute risks), in particular heavy rainfalls and coastal floods. The estimation of physical risk factors is based on public scientific data and fully replicable models. As per regulation, the risk assessment covers the full range of possible outcomes by providing an estimated probability distribution. Considering the firm actual vulnerability (i.e. whether adaptation solutions have already been implemented and in which cases they would be sufficient), the regulation requires to estimate the associated financial effects. These are assessed based on expert judgment, to account for firm-specific characteristics.

Based on a detailed, quantitative and fully ESRS-compliant methodology, we conclude that some of the assessed climate physical risks are material for the firm, as projected outcomes could exceed the loss threshold that the firm's management is willing to accept (risk appetite). At the same time, other risks are assessed as non-material for the firm, as implemented adaptation solutions are estimated to be sufficient to protect the farm even in a worst-case scenario.

While regulators cannot provide practical guidance applicable to all firms, given the specificity of their businesses, in this paper we implement a methodology which is fully compliant with relevant regulatory requirements, transparent, replicable, and. that could be applied to perform a materiality assessment for every ESG matter.

Quantitative assessment of the financial materiality of climate physical risks: a case study

Lucia Alessi, Andrea Giacomelli***

** European Commission – Joint Research Centre*

*** Ca' Foscari University of Venice*

Abstract:

We offer an applied approach to the double materiality assessment of environmental, social and governance (ESG) matters, which could serve as practical guidance to the 60K companies required by EU regulation (CSRD) to carry out this assessment. Focussing on the financial materiality of climate physical risks, due to its regulatory priority, we provide numerical examples, developed in compliance with all relevant regulatory requirements (ESRS). These examples are based on a generalised methodology, which allows to perform both impact and financial materiality assessments on any sustainability matter, adopting the most suitable sources of information: publicly available scientific data to perform fully transparent ESG risk estimates and expert judgment (of firm managers and/or advisors) to consider the significant idiosyncratic features characterising the financial effects of ESG matters.

Keywords: Sustainability reporting standards, double materiality assessment, ESG sustainability report, environmental sustainability, ESG risk management, climate physical risk, idiosyncratic forward-looking information.

JEL Classification: D81, G32, K32, Q51, Q54, Q56

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E-mail: lucia.alessi@ec.europa.eu, andrea.giacomelli@unive.it.

1. Introduction

The accounting literature has long debated on the concept of risk materiality. Essentially, the notion of materiality was introduced to increase transparency for investors. The general principle is that only risks that are not material, i.e. that are negligible, for a given company can be omitted from that company's disclosures, in order to provide investors with a complete picture. Originally, the concept of materiality only related to financial information. However, with the sustainability discussion becoming increasingly relevant, academics and policymakers are now paying more attention to the relevance of non-financial information, i.e. information on the environmental, social and governance (ESG) dimensions, for the proper assessment of financial risks.

In the context of sustainability, the discussion on risk materiality has recently focussed on the concept of 'double materiality'. This refers to need of considering both the 'outside-in' and the 'inside-out' perspectives for a comprehensive assessment of financially material risks. In particular, the 'outside-in' perspective, known as financial materiality, refers to the ESG risks that could materially affect a company's financial position, reputation, or strategic objectives. An example of such risks are so-called climate transition risks, i.e. risks related to the shift to a low-carbon economy where particular activities will need to be abandoned and the associated assets will become 'stranded'. Another example are so-called climate physical risks, related to the occurrence of natural disasters impacting e.g. a company's operations. The 'inside-out' perspective, called impact materiality, relates to the impact of a company's business on people and the environment. Such aspects are crucial to determine the scope of a company's sustainability reporting and, more broadly, to shape its strategy. However, what is most important to acknowledge is that the impacts of a company's activities on the society and the planet can also be financially material, as they are interconnected with the 'outside-in' risk dimension. Indeed, several companies have already faced financial consequences, e.g. in the form of fines or stock price reactions, following misconducts related to the ESG sphere.

The European Union has recognised the relevance of the double materiality assessment in the context of relevant regulation. The double materiality perspective was already present in the Non-Financial Reporting Directive (NFRD)[1], in particular in the context of reporting climate-related information. The Corporate Sustainability Reporting Directive (CSRD)[2], replacing the NFRD, fully incorporates the concept of double materiality. The CSRD's double materiality approach is a key aspect, aiming to improve the quality and comparability of sustainability reporting and enhance transparency for investors, stakeholders, and the public.

While the CSRD sets the overarching framework for sustainability reporting, the information that undertakings are required to report is specified in the European Sustainability Reporting Standards (ESRS, European Commission, 2023). The EFRAG, the technical advisory body in charge of developing draft ESRS for the European Commission, has also issued accompanying implementation guidance documents (EFRAG, 2024). Implementation guidance is provided in particular with respect to the materiality assessment. However, neither the ESRS nor the relevant implementing guidance document indicate any specific methodology to perform the double materiality assessment. In fact, the ESRS introduce the general principles underpinning the double materiality assessment and the

[1] Directive 2014/95/EU of the European Parliament and of the Council of 22 October 2014 amending Directive 2013/34/EU as regards disclosure of non-financial and diversity information by certain large undertakings and groups.

[2] Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting.

implementing guidance document defines the macro steps of the materiality assessment process, underlying that an undertaking has to define the details of every step based on its specific facts and circumstances.

Also, when looking at the academic literature, one struggles to find empirical studies.[3] In particular, to our knowledge, an approach to carry out a step-by-step financial materiality assessment has not been developed yet. The accounting literature has long debated on risk materiality, including in the context of audit (see e.g. Chong and Vinten, 1996), and concepts such as 'materiality thresholds' are well established. However, the literature on materiality and sustainability is very recent. One strand of it deals with ESG materiality from a conceptual or methodological angle.[4] For example, Moratis and Van Liedekerke (2024) emphasize that ESG materiality is a multidimensional concept, with temporal dynamics, hence firms may find it difficult to assess it in practice. Kakogiannis et al. (2023) propose a methodology to assess ESG materiality at a sector level, with a view to improve the robustness of ESG ratings by identifying ESG factors that are material for a given industry. Another strand of literature focuses on taking stock of the uptake of double materiality as an emerging practice at an aggregate level. In this respect, Shami (2023) and De Cristofaro and Gulluscio look at corporate reports from 2020 and from 2019-2021, when the double materiality concept was still in its infancy, while Dragomir et al. (2024) report evidence based on a sample of 20 Romanian companies. Some papers, such as Torelli et al. (2019) and Goettsche et al. (2023), look specifically at the application of the standards by the Global Reporting Initiative (GRI) and Sustainability Accounting Standards Board (SASB), respectively, investigating the role of stakeholder engagement and shareholder pressure in shaping a company's sustainability performance. From a legal perspective, Mezzanotte (2023) analyses legal risks associated with the double materiality assessment, with a focus on impact materiality, stemming from the company-stakeholders engagement process, the accuracy and completeness of reporting, and the uncertainty about the legal criteria for determining impact materiality. Finally, focussing on climate risk materiality, Gostlow (2020) and Matsumura et al. (2022) look at US companies' disclosures on physical risk, while Nielsen (2023) offers a case study on the assessment of climate transition risks, and Gourdel et al. (2024) look at the double materiality of both physical and transition risks for the euro area economy at an aggregate level.

The literature, from different angles, calls for adequate materiality assessment processes limiting room for discretional judgments. Against this background, in this paper we offer a practical approach to the materiality assessment by providing numerical examples, developed by considering all relevant regulatory requirements. This study is the first attempt to carry out the materiality assessment on the ground, in a context where around 60.000 companies[5] are precisely required to do so, but lack practical guidance.

For this study we focus on the financial materiality assessment of climate physical risks, owing to their universal relevance and for their importance from a policy perspective. Indeed, all firms in the scope of the CSRD are required to report on the outcome of their materiality assessment of the climate dimension. Moreover, the assessment of climate risks by the financial sector is comparatively rather advanced, as regulators and supervisors have included this among their priorities. In turn,

[3] See Fiandrino et al. (2022) for a systematic literature review on sustainability materiality research.

[4] See Adams et al. (2021) for a review of the literature on issues in applying double materiality.

[5] Around 50.000 EU companies are large enough to fall in the scope of the CSRD, plus around 10.000 non-EU companies with significant operations in the EU.

investors expect non-financial companies to carry out an assessment of the climate risks they are exposed to, including physical risks.

A first key aspect of the present study is that the data used on physical factors is exclusively public. In a context where 'physical risk solutions' are mushrooming, companies might be tempted to resort to commercial black boxes. However, it is of utmost importance that the assessment of any type of nature-related risk be based on scientific evidence and data, and fully transparent. Looking at climate physical risks in particular, elements such as the considered climate scenario and the granularity of the underlying disaster risk maps play a crucial role in determining the overall risk assessment, hence they should be clearly spelled out.

A second key aspect of the present study is that the information to estimate the financial effects of the physical risk factors is based on expert judgment, in order to properly account for idiosyncratic features, which are very relevant in this case. To assess firm-specific financial impacts, the most suitable source of information is structured expert judgment, which is the collection, through a formalized and tracked process, of the knowledge of relevant experts, such as firm managers and/or advisors.

The remainder of the paper is organized as follows. Section 2 describes the main regulatory requirements. Section 3 defines the object of the examples, i.e. the financial materiality assessment of physical risk factors, its motivations and the main features of the adopted financial materiality approach. Section 4 presents empirical examples. Section 5 concludes.

2. Regulatory requirements on the double materiality assessment

The two main regulatory sources for the double materiality assessment are the ESRS and the EFRAG Guidelines. The first set of ESRS has been adopted in 2023 and comprises two cross-cutting standards and 10 topical standards[6]. The two cross-cutting standards cover general requirements and formal rules for reporting (ESRS 1), and broad disclosure requirements (ESRS 2), including basic company data and information about the company's sustainability governance and strategy. ESRS 1 covers the double materiality assessment and requires that the topical standards be subject to it.

The 10 topical standards are structured as follows:

- ESRS E1 to E5: these standards cover the various dimensions of environmental sustainability, namely climate change, pollution, water and marine resources, biodiversity and ecosystems, and circular economy[7].
- ESRS S1 to S4: these standards cover dimensions related to social sustainability: own workforce, workers in the firm's value chain, impacts on communities, and impacts on consumers and end users of firm's products.
- ESRS G1: this standard relates to governance sustainability, i.e. to the corporate's policies on business conduct.

[6] Commission Delegated Regulation (EU) 2023/2772 of 31 July 2023 supplementing Directive 2013/34/EU of the European Parliament and of the Council as regards sustainability reporting standards.

[7] These 5 dimensions almost perfectly overlap with the 6 environmental objectives in which the EU Taxonomy for sustainable activities is structured, with the only difference of climate change mitigation and adaptation being grouped into one single standard.

2.1 ESRS 1

All sustainability topics that are subject to disclosure by firms are referred to as "*sustainability matters*". However, for a given firm certain sustainability matters are more relevant than others, due to its specific characteristics such as the type of business it runs, its location, the natural resources it depends on, etc. To allow firms to focus only on the most relevant sustainability issues, they are required to carry out a double materiality assessment. Out of a long list of sustainability matters, the firm is asked to disclose only the material ones (see paragraph 30 of ESRS 1).

Generally, if a firm concludes that a sustainability matter is non-material, it can voluntarily provide a brief explanation of the results of the materiality assessment, but is not obliged to do so. However, there is a single exception, which concerns climate change (covered in ESRS E1). Indeed, even if the firm concludes that climate change is not a material matter, it is required to give a detailed explanation of why it does not consider it material. In fact, with this exception the regulator introduces an order of priority among all sustainability matters: climate change must always be reported, hence a detailed materiality assessment is always required (see paragraph 32 of ESRS 1).

Definitions

ESRS 1 introduces the concept of double materiality by identifying with the term "*impact materiality"* all the relevant impacts that the firm generates on people or the environment, while it identifies with term "*financial materiality"* all the material sustainability matters that influence the financial performance of the firm (see paragraph 21 and 37 of ESRS 1).

With respect to impact materiality, it should be noted that both negative and positive impacts that the firm can generate must be disclosed. Moreover, not only current but also potential impacts need to be disclosed. With respect to potential impacts, they must be assessed with respect to the short, medium and long term, as business strategies may only generate effects over a particular time span[8] (see paragraph 43 of ESRS 1). For example, the effects of investments in energy efficiency improvements and emission reduction may only display their effects after several years. Finally, relevant impacts are not limited to those connected with the firm's own operations, but include those of the upstream and downstream value chain. Not to overburden reporting companies, disclosures on value chains are expected to be proportionate and relevant to the scale and the characteristics of the companies in the value chain, and the use of sector-averages and other proxies is allowed.

With respect to financial materiality, if a sustainability factor generates effects on the firm's financial performance, it must be taken into consideration both with respect to the risks it generates and the opportunities that the firm can pursue. Also in this case, the firm must not only take into consideration current risks and opportunities, but especially future ones, with reference to the short, medium and long term and the whole value chain. Finally, the effects of sustainability matters on the firm must be expressed directly in financial terms, with a quantification of the impacts on the firm's income statement or balance sheet (see paragraph 49 of ESRS 1).

Materiality assessment

[8] The short term is defined as the period adopted by the undertaking as the reporting period in its financial statements, the medium term spans from the end of the short-term reporting period to up to 5 years, while the long term corresponds to more than 5 years (see paragraph 77 of ESRS 1).

ESRS 1 specifically requires approaching impact materiality, wherever possible, from a *purely quantitative* point of view. This includes identifying the scale of the impacts generated by the firm, representing them with precise metrics and estimating the probability of occurrence (see paragraph 45 and 46 of ESRS 1).

The approach is the same with respect to financial materiality: the firm needs to *quantitatively* assess the potential magnitude of relevant risks and opportunities, and their probability of occurrence. In particular, risks and opportunities need to be valued in terms of deviations of relevant financial KPIs (e.g. future cash flows). A forward-looking perspective is essential, as the future will not look like the past with respect to the probability of materialization of particular risks and their severity (see paragraph 51 of ESRS 1).

The double materiality assessment methodology involves the specification of materiality thresholds, which can be quantitative and/or qualitative (see paragraph 42 of ESRS 1), to determine univocally which impacts, risks and opportunities are identified by the undertaking as material. With regard to environmental impacts (pillar E), the thresholds adopted in the technical screening criteria of the EU Taxonomy could be used for impact materiality; in particular, the substantial contribution thresholds allow to identify positive impacts, while the do no significant harm (DNSH) thresholds allow to identify negative impacts. To set financial materiality thresholds, the risk appetite and risk tolerance thresholds defined in the risk appetite statements can be directly adopted.

A very important aspect to consider is the interdependence among impacts, risks and opportunities. Indeed, a sustainability impact may be or become financially material as it may affect the undertaking's financial position, financial performance, cash flows, its access to finance or cost of capital over the short-, medium- or long-term (see paragraph 38 of ESRS 1). A typical example of this interdependence is the impact of a firm's emissions to air, water and soil. A high level of emissions is increasingly perceived negatively by firms' customers, and may trigger losses in terms of market share or fines.

Finally, ESRS 1 discusses the issue of the uncertainty surrounding forward-looking assessments. Indeed, contrary to backward-looking assessments where outcomes can be precisely measured, forward-looking assessments need to represent potential suffered risks and potential generated impacts in terms of ranges and probabilities (see paragraph 91 of ESRS 1). In other words, the regulation mandates the use of a probabilistic approach for the assessment of uncertain outcomes, considering the full range of possible outcomes. This is the traditional approach in risk analysis and all best practices (Enterprise Risk Management (ERM) Framework) and risk regulations (Basel, EBA Guidelines, Solvency, etc.), explicitly referred to in ESRS 1, adopt such probabilistic approaches. However, ESRS 1 requests to consider the probability of occurrence of the full range of possible outcomes, instead of just one event.

2.2 EFRAG Guidelines

Two key aspects in the EFRAG Guidelines regarding the double materiality assessment are the following: i) financial materiality must be conducted as part of the Enterprise Risk Management (ERM) process, and ii) the approach must be firm specific.

As regards financial materiality, the methodology and the process must refer to the best practice described in the principles of Enterprise Risk Management (ERM), which include policies, procedures, risk limits and risk controls ensuring adequate, timely and continuous identification, measurement, monitoring, management, mitigation and reporting of the risks at the business line, institution and consolidated or sub-consolidated levels[9]. In particular, risk assessment in the ERM framework is articulated in the following 4 main steps:

- 1 – Risk Identification: it should include both the forward-looking and the backward-looking perspectives.
- 2 – Risk Measurement: it is based on the estimation of the probability of risk factors occurrences and the severity of impacts on the form's KPIs.
- 3 – Risk Appetite Statement: allows to establish internal limits consistent with the firm's risk appetite and commensurate with its sound operation, financial strength, capital base (risk capacity) and strategic goals.
- 4 – Risk Monitoring: assesses the risk profile against the firm's risk appetite and against the firm's risk capacity The following condition has to hold: *Risk Profile ≤ Risk Appetite ≤ Risk Capacity.*

Having established the above principles for a sound risk assessment, EFRAG acknowledges that the set of relevant indicators and the overall severity assessment are idiosyncratic to each firm. Therefore, there is no single solution applicable to all undertakings in terms of process design and methodologies. For this reason, the EFRAG Guidelines do not provide quantitative examples of full assessment processes, which is the contribution of this paper.

3. Financial materiality assessment of climate-related physical risk factors

Given that the scope of application of the double materiality assessment in the CSRD is very broad (impact, financial, for three ESG pillars), this paper exhaustively exemplifies a single relevant topic. In particular, this paper focuses on examples about climate-related physical risks, due to its relevance from different points of view:

a) It cannot be ignored by any firm;
b) It has implications in terms of adaptation needs;
c) Climate change is the sustainability matter to which the CSRD attributes the highest priority.

Physical risk only requires a financial materiality assessment. For this reason, the examples we provide are only on this aspect.

ESRS E1 requires firms to assess the materiality of the predefined set of physical risk factors shown in the following table:

[9] See also the guidance on Internal Control over Sustainability Reporting (ICSR) by the Committee of Sponsoring Organizations of the Treadway Commission (CoSO) and the "Standard On Sustainability Assurance 5000, General Requirements For Sustainability Assurance Engagements" (ISSA 5000) proposed by the International Auditing and Assurance Standards Board (IAASB).

Classification of climate-related hazards (Source: Commission delegated regulation (EU) 2021/2139)				
	Temperature-related	**Wind-related**	**Water-related**	**Solid mass-related**
Chronic	Changing temperature (air, freshwater, marine water)	Changing wind patterns	Changing precipitation patterns and types (rain, hail, snow/ice)	Coastal erosion
	Heat stress		Precipitation or hydrological variability	Soil degradation
	Temperature variability		Ocean acidification	Soil erosion
	Permafrost thawing		Saline intrusion	Solifluction
			Sea level rise	
			Water stress	
Acute	Heat wave	Cyclones, hurricanes, typhoons	Drought	Avalanche
	Cold wave/frost	Storms (including blizzards, dust, and sandstorms)	Heavy precipitation (rain, hail, snow/ice)	Landslide
	Wildfire	Tornado	Flood (coastal, fluvial, pluvial, ground water)	Subsidence
			Glacial lake outburst	

It should be noted that the Taxonomy Regulation (European Parliament and Council, 2020) requires to assess the same set of physical risk factors with regards to the adaptation objective (Objective 2). This matter is therefore relevant because it covers not only CSRD compliance, but also Taxonomy Regulation compliance.

Physical risk factors are classified in two main categories:

- **Chronic risk factors:** climate-related physical risks resulting from long-term shifts in climate patterns, such as temperature changes, and their effects on rising sea levels, reduced water availability, biodiversity loss and changes in land and soil productivity.
- **Acute risk factors:** climate-related physical risks resulting from extreme events and natural hazards such as storms, floods, wildfires and heatwaves.

In section 4, we provide empirical examples of financial materiality assessments for both chronic and acute risks. For both categories, particular risks may turn out as material or non-material for the firm, as we show.

3.1 The adopted financial materiality approach: main features

In each of these four examples, the assessment of the physical risk factors' financial materiality is performed by applying the following Generalized two-steps Materiality Approach (GMA) proposed by Giacomelli (2024), which applies to perform both impact and financial materiality assessment in compliance with ESRS requirements.

GMA Step 1 – Analysis of the cause

a) Definition of future time horizon (adopting ESRS 1 requirements, art. 74 and 77).

b) Identification of the cause indicator (adopting ESRS 1 requirements, art. 43 and 49).

c) Collection of information on the cause indicator and projections.

d) Estimate of the cause indicator probability distribution (adopting ESRS 1 requirements, art. 91).

e) Consistency check on the estimated probability distribution.

GMA Step 2 – Analysis of the effect

f) Identification of the effect indicator (adopting ESRS 1 requirements, art. 43 and 49).

g) Setting of materiality thresholds (adopting ESRS 1 requirements, art. 42).

h) Quantification of the effect (adopting ESRS 1 requirements, art. 45, 46 and 51).

i) Estimate of the effect indicator probability distribution (adopting ESRS 1 requirements, art. 91).

j) Judgment on materiality.

k) If the effect is assessed as material, development of the related action plan (adopting ESRS 2 requirements, art. 66 – 69).

For further information on the theoretical characteristics of this GMA, see Giacomelli (2024).

What follows focuses on the application of the GMA for the financial materiality assessment of physical risk factors.

GMA Step 1 – Analysis of the cause (ESG risk factor)

a) Definition of future time horizon: relevant time horizon to be considered in the firm's ESG risk factor assessment. For example, in the case of chronic impacts of climate change, the relevant horizon is the long term.

b) Identification of the cause indicator: indicator measuring the possible range of intensity for the relevant ESG risk factor[10], indicated with $\boldsymbol{x}_{ESG}$. This can be related, for example, to temperature, precipitation, wind speed, etc.

c) Collection of information on the cause indicator and projections: information consists of a statistical sample on the relevant ESG risk factor for a particular firm.

[10] There are two kinds of ESG risk factors: direct and triggered by impacts (feedback)

In the climate scientific literature, models for the analysis and projection of climate factors are classified into two main categories: process-based dynamical models[11] and statistical models[12]. The former are based on systems of equations representing the functioning of the meteorological system and can be at a regional or global scale. The latter are mainly used for downscaling low regional resolution models or for forecasts on relatively short periods, from few weeks to few years. In this paper we adopt statistical models that are robust and simple to apply, namely univariate dynamic models applied to high resolution data. As outcome of this step, we obtain the expected future levels of e.g. temperature, precipitation etc. over the relevant time horizon.

d) Estimate of the cause indicator probability distribution: the probability distribution of $\boldsymbol{x}_{ESG}$ allows to calculate the probability of occurrence (or likelihood) of the following: i) the baseline scenario, i.e. the most probable event, where the ESG risk factor takes the modal value, and ii) the deviations from the baseline scenario. While the statistical models adopted under point c) provide projections in terms of reliable point estimates, they are not suitable to derive a probability distribution of future outcomes, as they typically rely on normality and homoscedasticity assumptions which are not verified in climate data. At the same time, in climate risk modelling, it is not possible to adopt a standard parametric hypothesis on a risk factor distribution, given the asymmetry of the stochastic processes that describe the observations of several climate risk factors. In order to overcome this modelling issue, in this paper the prospective probability distribution with reference to the relevant time horizon and for the selected physical indicator is estimated using the KnowShape platform[13], as this solution adopts a hypothesis-free approach on the risk factor probability distributions. As outcome of this step, we obtain the probability attached to each possible level of e.g. temperature, precipitation, etc. over the relevant horizon.

e) Consistency check on the estimated probability distribution: tests whether the different features of the probability distribution for $\boldsymbol{x}_{ESG}$ (mode, tails, skewness, etc.) are consistent with the projections derived under point c). For example, if the expected value of the probability distribution is statistically close to the projection of the statistical model.

GMA Step 2 – Analysis of the effect (financial KPI)

f) Identification of the effect indicator: this is a firm's financial KPI, indicated with y_{FIN}, affected by the relevant ESG risk factor. For example, it could be related to turnover or a particular class of expenses.

g) Setting of materiality thresholds: thresholds, to set on the domain of the financial KPI y_{FIN}, defining:

- Risks that the firm's management do not want to take based on their risk appetite.
- Opportunities to seize.

[11] A review of these models can be found in: Palmer et al. (2003), Troccoli (2010), Meehl et al. (2021)

[12] A review of these models can be found in: Barnston and Smith (1996), Mason and Baddour (2008), Eden et al. (2015), Totz et al. (2017)

[13] KnowShape, a research spin-off of the University of Venice, has developed an IT platform to perform forward looking ESG assessments adopting a hypothesis-free approach for modelling both historical data and structured expert judgment. For more information see *www.knowshape.com*

h) Quantification of the effect: this step involves the estimation of the severity function, which explains how the different intensities of the risk factor affect the financial KPI selected in point f). The severity function is modelling the domain of y_{FIN} and describes:

- The target level for y_{FIN}: this is calculated on the basis of the ESG risk factor baseline scenario.
- Deviations of y_{FIN} from the target level: these are unexpected deviations associated with deviations of the ESG risk factor from its baseline[14].

The severity function varies across firms based on idiosyncratic characteristics; hence, it is not possible to adopt universally valid assumptions on its functional form. To account for firm-specific features, the most suitable source of information is structured expert judgment. This is the collection, through a formalized and tracked process, of the knowledge of the experts working in the firm (firm managers and/or advisors). We resort to the KnowShape platform also for the estimation of the severity function with reference to the relevant time horizon for the selected financial KPI, as this solution also offers a hypothesis-free approach on severity functions for modelling structured expert judgment. As outcome of this step, one obtains the full range of possible future values of the relevant financial indicator.

i) Estimate of the effect indicator probability distribution: this is the severity distribution, describing the probability attached to each value of the financial KPI y_{FIN}, and is derived as a transformation of the probability distribution of the ESG risk factor $\boldsymbol{x}_{ESG}$ (estimated under step d). As outcome of this step, one obtains the likelihood of the possible financial outcomes requested by ESRS 1 art. 91.

j) Judgment on materiality: a sustainability matter is financially material if there is a non-zero probability that the risks to avoid and/or the opportunities to seize will materialize[15]. This probability, to be computed on the basis of the probability distribution estimated at point i), is attached to the event that the financial KPI y_{FIN} will exceed the materiality threshold set under point g).

k) If the effect is assessed as material, development of the related action plan: the plan has to include the following:

- The assumptions on the ESG risk factor (baseline scenario) as per point d), used to set the financial KPI target as per point h), as well as explanations on how the firm plans to reach the financial KPI target.
- How to manage the possible ESG risk factor deviations from the baseline scenario in order to avoid their critical financial effects, by specifying which interventions to adopt.

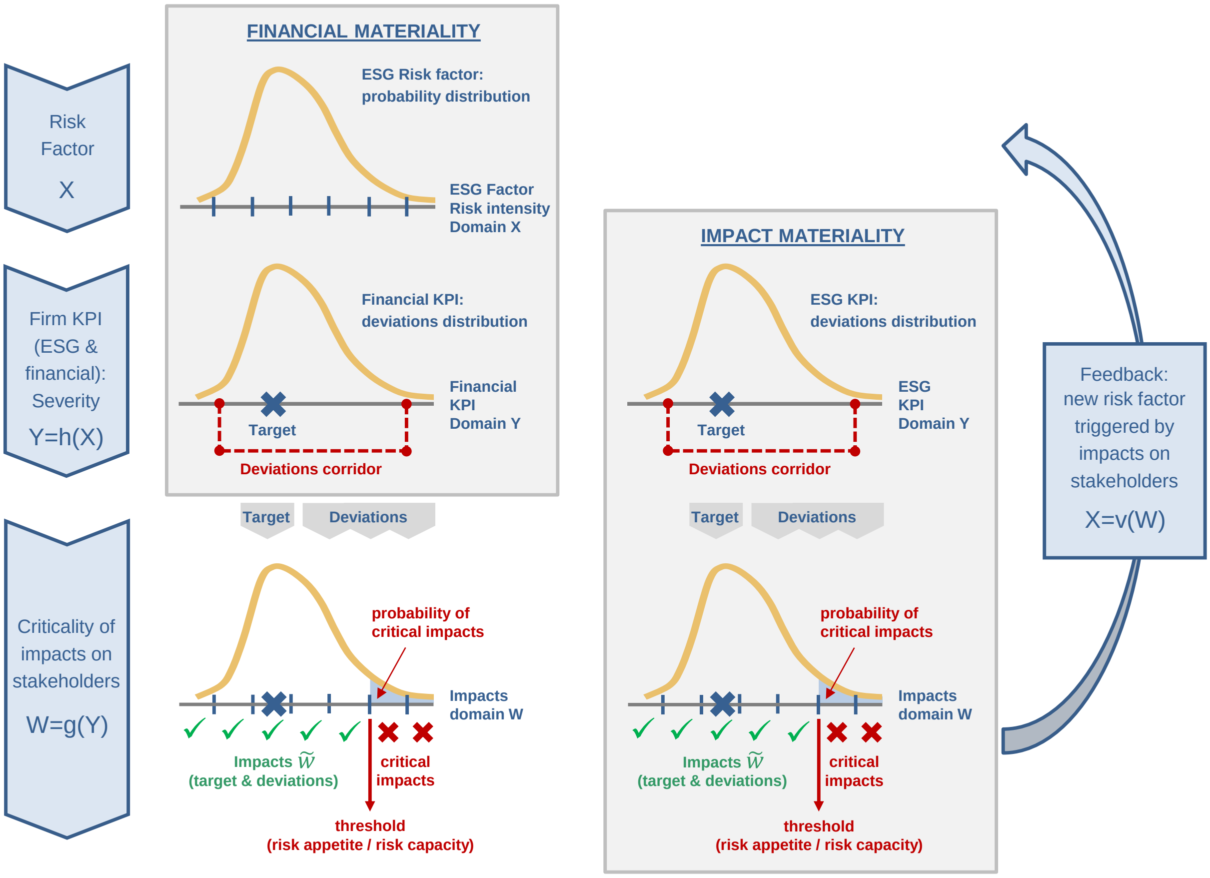
The first point is an outcome of the enterprise financial planning process. The second point is an outcome of the enterprise risk management process.

The Generalized two-steps Materiality Approach (GMA) is summarized in the following figure:

[14] This financial materiality analysis has to be carried out on the entire domain of the ESG risk factor $\boldsymbol{x}_{ESG}$, in order to exhaustively analyse all the possible financial deviations the firm can suffer.

[15] Based on the regulation, a sustainability event is defined as financially material if it allows the attainment of a firm's financial target or if it may imply negative financial effects.

Figure 1: Variables and causal functions involved in the double materiality approach



This generalized two-steps materiality approach, which considers the full range of risk factor intensities and the related full severity range, in compliance with par. 91 of ESRS 1, is different from the traditional "frequency-severity" approach, which considers only the probability of occurrence of one single risk event and one single related expected severity value. This latter approach is in fact not compliant with ESRS 1 and does not allow in many cases to identify the materiality of the risks and relevant adaptation plans. Therefore, the generalized two-step materiality approach can be interpreted as a "full range" evolution of the traditional "frequency-severity" approach. For further details and a numerical example on the comparison between the two approaches, see Giacomelli (2024).

4. Empirical examples: application of a general materiality assessment approach

The examples presented in this section refer to a real project, which involves the construction of an educational farm for families and schools on a small island in the Northern Lagoon of Venice[16]. This

[16] This project is part of the initiatives promoted by the Venice World Sustainability Capital Foundation (*https://vsf.foundation/en/*). The Venice Sustainability Foundation was established to offer that the history of resilience of the City of Venice – its continuous and ingenious search for balance between the needs of a community of inhabitants and

island has been abandoned and left uncultivated for at least 25 years. The farm intends to restore over 50 crops and livestock belonging to the centuries-old history of the Lagoon, identified through historical research conducted on original documents from the Venice State Archive. This ESG project aims at protecting biodiversity, an objective both in the EU Taxonomy and ESRS E4.

The project is highly exposed to climate risks, as described below.

We have selected different physical risks factors, out of the regulatory list, for each of the four empirical examples.

In particular, the four physical risk factors covered in the four financial materiality assessment cases are as follows:

- **Case 1: chronic risk factor = "Changing temperature – air":** the change in air temperature is a relevant chronic physical risk factor, since a significant increase in air temperature compared to the current level can damage the island's crops and, in general, severely alter the state of biodiversity and the ecosystem.
- **Case 2: chronic risk factor = "Sea level rise":** sea level rise is a relevant chronic physical risk factor, as the island is located within the Venice Lagoon, an extremely vulnerable ecosystem to sea level rise. A significant rise in sea levels could threaten the very existence of the island.
- **Case 3: acute risk factor = "Heavy precipitation – rain":** the occurrence of extreme rainfall phenomena is an acute physical risk factor of interest, as heavy rainfall can damage the island's crops and, in general, severely alter the state of biodiversity and the ecosystem.
- **Case 4: acute risk factor = "Flood – coastal":** the risk of exceptional high tides is acute and represents a typical phenomenon of the Venice Lagoon, which in the past has caused serious damages to the natural and historical heritage (for example the "Acqua Granda" of 2019, when the tide reached the level of around 190 centimetres above the average level). The risk factor is relevant as the island is located within the Venice Lagoon. An exceptional high tide like the one that occurred in 2019 could cause serious damages to assets and nature.

4.1 Case 1: chronic risk [Changing temperature – air]

STEP 1: Analysis of the cause

a) <u>Definition of future time horizon</u>:

Changes in air temperature are a chronic physical risk factor. Chronic risks are determined by long-term changes in climate patterns; for this reason, the "Changing temperature - air" risk factor is assessed over a long-term time horizon (>5 years) 01/01/2024 - 31/12/2030.

b) <u>Identification of the cause indicator (Physical risk factor):</u>

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the particular environment that hosts it – as a source of inspiration for the realization of a sustainable future, resilient to complex existential threats. The Foundation is promoting a plan of sustainable territorial development that can be a reference for other cities worldwide.

In order to measure the "Changing temperature - air" risk factor, the "Average annual air temperature" has been identified as suitable for analysing the long-term trend of air temperature.

The risk factor indicator “air temperature change” is intended as the change at 31/12/2030 of "Average annual air temperature" compared to the last available observation referring to 31/12/2022.

c) Collection of information on the cause indicator and projections:

The following public scientific data have been collected for the “Average annual air temperature”:

- Air temperature at 2m (°C) - average annual value.
- Source: Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto (ARPAV)[17].

For details on data see Appendix 6.1.

Given the long-term time horizon of the analysis, we need to consider the trend component of the stochastic process that describes the observations on this risk factor.

Adopting a univariate dynamic statistical model[18], the statistical analyses performed on these data produced the following results:

- Statistical model specification for projecting the average annual air temperature:

$$AirTemp_t = -114.56 + 0.06399Year_t + \varepsilon_t$$

  The results of the model specification are fully reported in Appendix 6.1.

- Statistical model’s projections of average temperatures until 31/12/2030:

$$MIN = 14.50\ °C$$

$$MODE = 15.34\ °C$$

$$MAX = 16.22\ °C$$

  Where:

  MIN = Modal value ($MODE$) minus the maximum observed negative deviation from the trendline[19].

  $MODE$ = Trend value at 31/12/ 2030.

[17] *Veneto Regional Agency for Environmental Protection.* ARPAV is responsible for the environmental supervision and control of the Veneto region with the purpose of ensuring the health of the population and the environmental safety of the territory. Furthermore, ARPAV monitor, process and disclose environmental data that can be freely accessed.

[18] For motivations, see Section 3.1.

[19] "Maximum negative deviation from the trendline" means the maximum negative difference in the entire sample period between the value observed in a given year and the trend value in the same year.

MAX = Modal value ($MODE$) plus the maximum observed positive deviation from the trendline[20].

The projections of the risk indicator "air temperature change" at 31/12/2030 are obtained by comparing the statistical model's projections of the average annual air temperature to the trend value at 31/12/2022, equal to 14.83 °C:

$$MIN = -0.33 \ °C$$

$$MODE = +0.51 \, °C$$

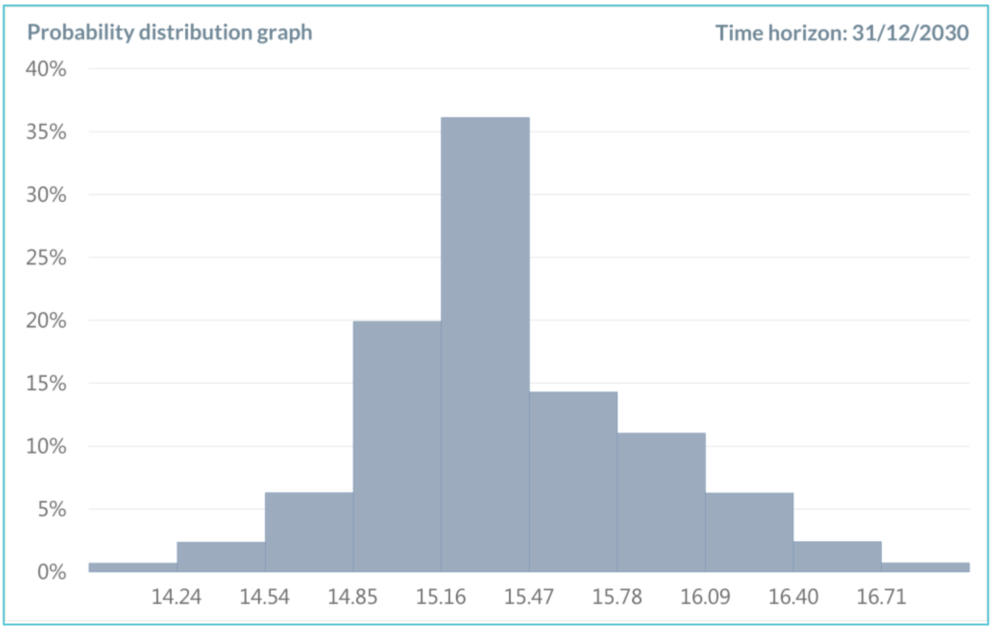
$$MAX = \ +1.39 \, °C$$

It should be noted that from 1994 to 2022 the average annual temperature increased from 13.9 °C to 15.1 °C, i.e. +1.2 °C in 28 years. According to the statistical model's projections, it is possible that the average annual temperature will go up to 16.22 °C in 2030, with an increase of +1.39 °C in just 8 years from the last available data. In a situation where average temperatures are already high, an increase of up to +1.39 °C could cause serious damages to the most fragile crops.

The risk indicator projections will be used in point e) to evaluate their consistency with the prospective probability distribution of the risk indicator.

d) Estimate of the cause indicator probability distribution:

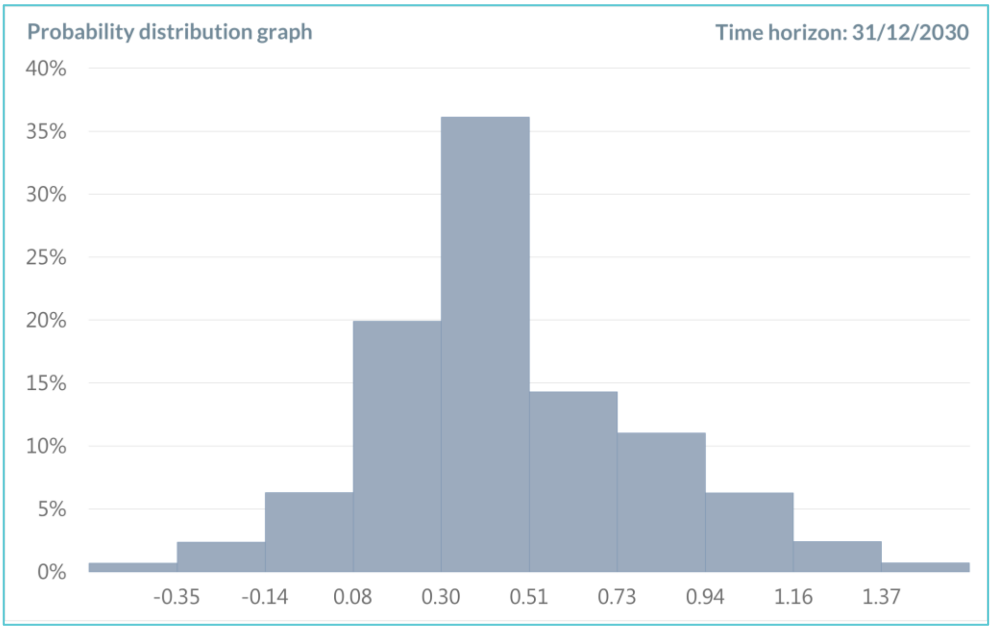
The estimate of the distribution referred to the average temperature level, adopting a hypothesis-free approach on the risk factor probability distribution implemented in the KnowShape platform[21], is represented in the figure below.



[20] "Maximum positive deviation from the trendline" means the maximum positive difference in the entire sample period between the value observed in a given year and the trend value in the same year.

[21] For motivations, see paragraph 3.1.

The estimate of the distribution referred to the physical risk factor indicator, constituted by "air temperature change" at 31/12/2030 compared to the trend value at 31/12/2022, is represented in the figure below.



This distribution satisfies the full range and likelihood requirements on risk factors that are required by ESRS 1. Based on the estimated probability distribution, the most likely interval for the future average temperature is between 15.16 and 15.47 °C, which implies a temperature increase between 0.3 and 0.5 °C, with a probability of around 35%.

e) Consistency check on the estimated probability distribution:

In this substep we compare the projections of the statistical model (point c) and the characteristics of the risk indicator distribution (point d) in order to verify their consistency.

As regards the distribution of the average annual air temperature, the projected minimum value is equal to 14.50 °C. Consistently, the distribution associates only a residual probability to values lower than 14.50 °C. The projection of the maximum value is equal to 16.22 °C, and the distribution consistently assigns only a residual probability to values greater than 16.22 °C. Finally, the projection of the modal value is equal to 15.34 °C while the distribution has a modal range between 15.16 °C and 15.47 °C.

As regards the distribution of the risk factor "changes in the average annual air temperature", the projection of the minimum value is equal to -0.33 °C, and the distribution consistently assigns only a residual probability to values lower than -0.33 °C. The projection of the maximum value is equal to +1.39 °C and the distribution highlights a residual probability for values greater than +1.39 °C. Finally, the projection of the modal value is equal to +0.51 °C while the distribution has a modal range between +0.30 °C and +0.51 °C. Hence, the projections and the estimated probability distribution are consistent.

STEP 2: Analysis of the effect

f) Identification of the effect indicator (Financial KPI):

The increase in average temperatures in the long term can cause serious damages to crops with consequent negative effects on the farm's production capacity. Therefore, in order to measure the severity of the risk factor, the following financial KPI has been identified: "percentage turnover change resulting from the decrease in production capacity".

g) Setting of materiality thresholds (Risk appetite):

The farm's management is willing to absorb changes in turnover of up to -35%. Negative deviations in turnover greater than -35% represent critical deviations that can cause serious consequences for the business continuity of the firm itself. Therefore, the materiality threshold is set at a change in turnover equal to -35%. This risk appetite statement meets the quantitative threshold requirements required by ESRS 1.

h) Quantification of the effect (Severity function):

The estimate of the severity function, based on structured expert judgment (firm managers and/or advisors) collected through the KnowShape platform[22], is described below:

- Variations lower than +0.85 °C, corresponding to average temperatures lower than 15.68 °C:
  - Turnover change = 0%.
  - Motivation: average temperatures lower than 15.68 °C would guarantee a sufficiently cold climate in winter and a temperate summer, hence there would be no negative impacts on both winter crops (violet artichoke called *castraùra*, pumpkin called *zucca del collo torto* and potato called *primaticcia*) and summer ones (*Dorona* grapevine and common cucumber). Turnover would not be impacted.

- Variations between +0.85 °C and +1.39 °C, corresponding to average temperatures between 15.68 °C and 16.22 °C:
  - Turnover change = -30% (mean value of the effects related to the relevant interval of risk factor intensities).
  - Motivation: the most fragile summer crops (*Dorona* grapevine and common cucumber) would be impacted by particularly hot average summer temperatures. This would lead to a contraction in production and a subsequent negative change in turnover of -30%.

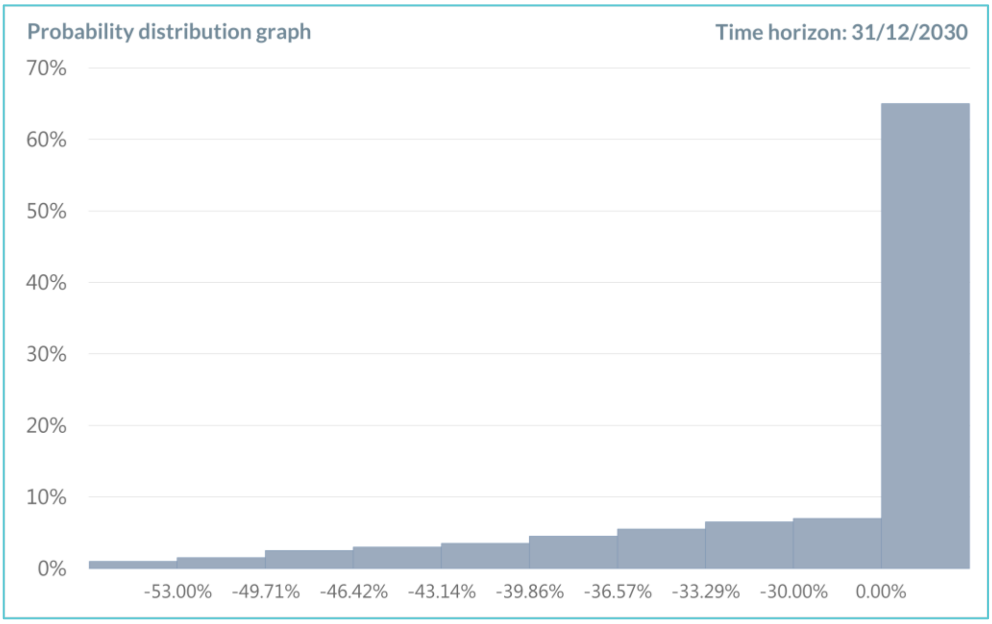
- Variations higher than +1.39 °C, corresponding to average temperatures higher than 16.22 °C:
  - Turnover change = -53% (mean value of the effects related to the relevant interval of risk factor intensities).
  - Motivation: such a high average annual temperature for local standards would generate negative impacts both on summer crops and on winter crops. Excessively hot summers and excessively mild winters would generate a contraction in winter and summer production, leading to a consequent negative change in turnover of -53%.

This estimate of the severity function satisfies the full range requirements (for the possible different intensities of the risk factor) that are required by ESRS 1.

[22] For motivations, see paragraph 3.1.

i) <u>Estimate of the effect indicator probability distribution (Financial KPI distribution)</u>:

The functional transformation of the risk factor distribution into the severity distribution is a necessary step to calculate the probability that financial KPI values lower than the identified materiality threshold will occur. The estimate represented in the figure below is calculated using the KnowShape platform and based on the risk factor distribution (point d) and the severity function (point h). The estimate represented in the figure below satisfies the full range and likelihood requirements required by ESRS 1.



j) <u>Judgment on materiality (Financial materiality of physical risk factor):</u>

With a horizon until 31/12/2030, the probability of observing negative changes in turnover lower than -35% (materiality threshold) obtained from the severity distribution is very significant and equal to 28%. The negative change in turnover equal to -35% occurs for variations in the average temperature greater than +0.85 °C but lower than +1.39 °C. The risk factor is therefore material and adaptation solutions must be identified to mitigate its prospective impacts.

k) <u>If the effect is assessed as material, development of the related action plan (Adaptation plan to physical risk):</u>

Given that the "Changing temperature - air" risk factor is material, an action plan must be formulated. In this plan, adaptation solutions are defined to manage the possible risk factor deviations in order to avoid their critical financial effects. The adaptation solutions identified are the following:

1. Shade nets: shade nets are an effective method of reducing outdoor temperatures. Shade nets can be installed and used during summer periods reducing direct exposure to the sun

and, consequently, temperatures. Shade nets can reduce external temperatures from a minimum of 5.5 °C to a maximum of 8.3 °C, ensuring significant protection for crops.

2. Soil mulching: mulching is an agricultural practice that consists of applying a layer of organic or inorganic material to the surface of the soil. This layer helps conserve soil moisture, reducing the need for watering and helping plants survive high temperature.
3. Biostimulants: biostimulants are substances or microorganisms that, applied to plants or soil, can improve plant nutrition, tolerance to thermal stress and crop quality.

These solutions, applied together, make it possible to protect crops from variations in average annual temperature exceeding +0.85 °C. In this way, there would be no negative impacts on both winter crops and summer ones. Therefore, turnover would not be impacted.

4.2 Case 2: chronic risk [Sea level rise]

STEP 1: Analysis of the cause

a) Definition of future time horizon:

As a chronic physical risk factor, the "Sea level rise" risk factor is assessed over a long-term time horizon (>5 years) 01/01/2024 - 31/12/2030.

b) Identification of the cause indicator (Physical risk factor):

A suitable measure for the "Sea level rise" risk factor is the "Annual rise of the average sea level".

c) Collection of information on the cause indicator and projections:

The following public scientific data have been collected for the “Annual rise of the average sea level”:

- Annual rise of the average sea level (cm). The rise is assessed with respect to the 1897 hydrographic zero of Punta della Salute (ZMPS).
- Source: Istituto superiore per la protezione e la ricerca ambientale (ISPRA)[23].

For details on data see Appendix 6.2.

Also in this case, one needs to analyse the trend component of the stochastic process that describes the observations on this risk factor, which we do by applying univariate dynamic statistical models to high resolution data.

The statistical analyses produced the following results:

- Statistical model specification for projecting the annual rise of the average sea level:

$$SeaLevel_t = -478.27 + 0.25262Year_t + \varepsilon_t$$

[23] *Italian Institute for Environmental Protection and Research*. ISPRA deals with environmental protection, including marine protection, environmental emergencies and research. ISPRA is also the guidance and coordination body of the Regional Agencies for Environmental Protection (ARPAs) and cooperates with the European Environment Agency (EEA).

The results of the model specification are fully reported in Appendix 6.2.

- Statistical model's projections until 31/12/2030 for sea level rise:

$$MIN = 24.04\ cm$$

$$MODE = 34.56\ cm$$

$$MAX = 45.56\ cm$$

Where:

MIN = Modal value ($MODE$) minus the maximum observed negative deviation from the trendline[24].

$MODE$ = Trend value at 31/12/ 2030. Annual average sea level growth relative to the ZMPS.

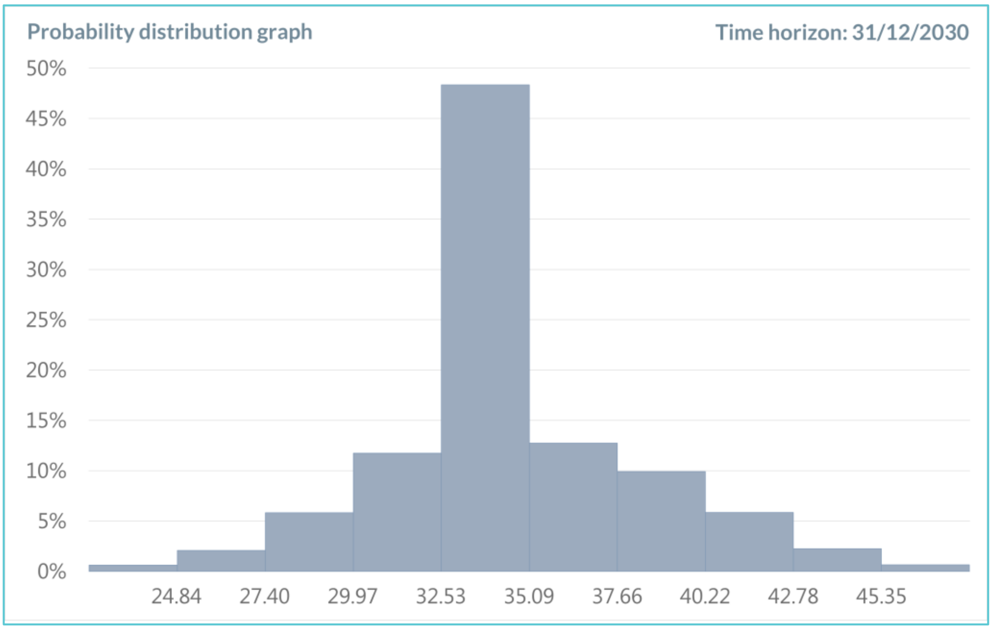
MAX = Modal value ($MODE$) plus the maximum observed positive deviation from the trendline[25].

These projections will be compared in point e) with the prospective probability distribution of the risk indicator.

d) <u>Estimate of the cause indicator probability distribution:</u>

As in the previous case, we use the KnowShape platform owing to its hypothesis-free approach on the risk factor probability distributions.

The estimated distribution is shown in the figure below.



[24]"Maximum negative deviation from the trendline" means the maximum negative difference in the entire sample period between the value observed in a given year and the trend value in the same year.

[25]"Maximum positive deviation from the trendline" means the maximum positive difference in the entire sample period between the value observed in a given year and the trend value in the same year.

Again, this distribution for the physical risk factor satisfies the full range and likelihood requirements on risk factors that are required by ESRS 1. It shows that the most likely scenario, with around 50% probability, is a sea level increase by between 32.5 and 35 cm by 2030.

e) Consistency check on the estimated probability distribution:

By comparing the projections of the statistical model (point c) and the characteristics of the risk indicator distribution (point d) one can verify their consistency. The projection of the minimum value is equal to 24.04 cm, and the distribution highlights only a residual probability for values lower than 24.04 cm. The projection of the maximum value is equal to 45.56 cm, and the distribution highlights only a residual probability for values greater than 45.56 cm. Finally, the projection of the modal value is equal to 34.56 cm, which is included in the modal interval of the probability distribution. Hence, the projections and the estimated probability distribution are consistent.

STEP 2: Analysis of the effect

f) Identification of the effect indicator (Financial KPI):

Rising sea levels could damage the island's banks, making it difficult to protect the internal land from the infiltration of brackish water. In these cases, it would be necessary to adapt the island's banks by raising them. Therefore, in order to measure the severity of the risk factor, the following financial KPI has been identified: "Costs for banks' adaptation".

g) Setting of materiality thresholds (Risk appetite):

The farm's management is willing to sustain costs for banks' adaptation of up to +50% of ordinary maintenance costs. Greater costs for banks' adaptation represent critical deviations that can cause serious consequences for the business continuity of the firm itself. Therefore, the materiality threshold is set at costs for banks' adaptation of up to +50% of ordinary maintenance costs. This risk appetite statement meets the quantitative threshold requirements in ESRS 1.

h) Quantification of the effect (Severity function):

As in the previous case, the estimate of the severity function is based on expert judgment collected through the KnowShape platform. The result is as follows:

- For all intensities of the risk factor:
  - Costs for banks' adaptation = 0.
  - Motivations: on the basis of scientific data and in relation to the time horizon 31/12/2030, the worst-case scenario is a sea level rise of approximately 45.56 cm compared to the ZMPS, corresponding to the maximum positive deviation from the expected (trend) value. The island has recently undergone works to restore the margins of the banks. The safety levels guaranteed by the restoration works are equal to +183.56 cm on the north side and +143.56 cm on the south side with reference to the ZMPS. Therefore, the restoration works protect the island even in the worst-case scenario.
    Hence, the estimate of the severity function is equal to zero for all possible intensities of the risk factor.

i) Estimate of the effect indicator probability distribution (Financial KPI distribution):

The costs for banks' adaptation are zero for all intensities of the risk factor. Hence, the severity distribution is entirely concentrated on the value 0 (the severity value equal to 0 has a probability equal to 1).

j) Judgment on materiality (Financial materiality of physical risk factor):

Given that, thanks to the restoration works, the financial KPI is always below the materiality threshold (the probability of exceeding the threshold is null), the risk factor is assessed as non-material.

k) If the effect is assessed as material, development of the related action plan (Adaptation plan to physical risk):

Given that the risk factor is assessed as non-material, it is not necessary to develop an action plan.

4.3 Case 3: acute risk [Heavy precipitation – rain]

STEP 1: Analysis of the cause

a) Definition of future time horizon:

Heavy rain precipitation is an acute physical risk factor. Acute physical risks arise from short-term extreme weather events; for this reason, the "Heavy precipitation - rain" risk factor is assessed on a short-term time horizon (1 year) with reference to 31/12/2024.

b) Identification of the cause indicator (Physical risk factor):

In order to analyse the phenomenon of heavy precipitation events, climate change research agencies mainly rely on the study of maximum daily precipitation values. For instance, the Euro-Mediterranean Centre on Climate Change (CMCC) analyses the change in maximum daily precipitation values[26], the US Environmental Protection Agency (EPA) computes the percentage of total precipitation of a particular location in a given year resulting from one-day extreme events[27] while the Intergovernmental Panel on Climate Change (IPCC) mainly analyses changes in indices of one-day or five-days precipitation amounts using global and regional studies[28].

In the context of enterprise risk management, the above indicators cannot be directly used, as they do not allow to directly explain the financial effects generated by the physical phenomenon. Indeed, the indicator that describes the physical risk factor must be directly linked to the explanation and interpretation of the severity through the estimation of the severity function. In particular, maximum daily values cannot be directly used since the quantity of water rained in a single day is not sufficient for the evaluation of its financial effect, as it is also relevant whether

[26] See: *https://www.cmcc.it/it/analisi-del-rischio-i-cambiamenti-climatici-in-italia*

[27] See: *https://www.epa.gov/climate-indicators/climate-change-indicators-heavy-precipitation*

[28] See: *https://www.ipcc.ch/report/ar6/syr/*

in the previous or subsequent days other precipitation phenomena concurred to aggravate the situation (flooding of crops on the island).

Therefore, the following risk factor indicator has been identified: "maximum millimetres of water rained within a 7-day window in a month". This indicator is suitable to analyse the temporal persistence of the precipitation phenomenon that causes the flooding of crops on the island.

c) <u>Collection of information on the cause indicator and projections</u>:

The following public scientific data have been collected for the "maximum millimetres of water rained within a 7-day window in a month":

- Daily precipitation measurements (mm)
- Source: ARPAV

For details on data see Appendix 6.3.

"Heavy precipitation - rain" risk factor is an acute risk factor. Differently from chronic risks, acute risks can have significant impacts even in the short term. For this reason, instead of analysing the trend, it is fundamental to perform a statistical analysis of extreme peaks, which are particularly harmful, as well as a heteroskedasticity analysis (dynamic volatility) in order not to underestimate the extreme tails.

Adopting univariate dynamic statistical models[29], the statistical analyses performed on these data produced the following results:

- Statistical model specification for projecting the maximum millimetres of water rained within a 7-day window in a month:

$$HeavyRain_t = 52.0656 + \varepsilon_t$$

  The results of the model specification are fully reported in Appendix 6.3.

- Statistical model's projections on the time horizon 31/12/2024 of the maximum millimetres of water rained within a 7-day window in a month:

$$MIN = 1.6\, mm$$

$$MODE = 52.0656\, mm$$

$$MAX = 165\, mm$$

  Where:

  MIN = Time series minimum value.

  $MODE$ = Expected value (model's constant value).

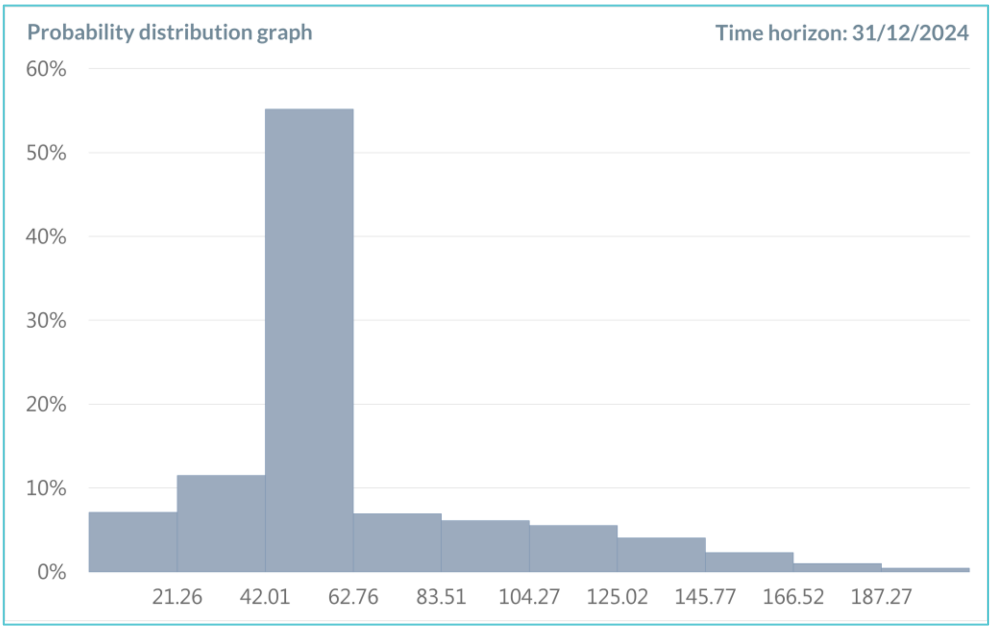
  MAX = Time series maximum value.

[29] For motivations, see paragraph 3.1

Since the "Heavy precipitation - rain" risk factor is an acute risk factor, it is necessary not to underestimate its extreme peaks. Therefore, for the statistical projections of the minimum (MIN) and maximum (MAX) values, the time series minimum and maximum values have been used.

d) Estimate of the cause indicator probability distribution:

As in the previous cases, we use the KnowShape platform owing to its hypothesis-free approach to estimate the physical risk factor probability distributions. The estimate of the distribution is represented in the figure below:



The most likely outcome, with 55% probability, is that the maximum millimetres of water rained within a 7-day window will range between 42 and 63.

e) Consistency check on the estimated probability distribution:

Comparing the projections of the statistical model (point c) with the characteristics of the risk indicator distribution (point d), the projection of the minimum value is equal to 1.6 mm, and the distribution highlights a residual probability for values lower than 1.6 mm. The projection of the maximum value is equal to 165 mm, and the distribution highlights a residual probability for values greater than 165 mm. Finally, the projection of the modal value is equal to 52.0656 mm while the distribution has a modal range between 42.01 mm and 62.76 mm. Hence, the projections and the estimated probability distribution are consistent.

STEP 2: Analysis of the effect

f) Identification of the effect indicator (Financial KPI):

The occurrence of intense and prolonged precipitation events for several consecutive days can generate serious damages to the farmland because it would be difficult for the soil to rapidly drain the water in excess. During such intense and prolonged precipitation events, land maintenance operations would be necessary in order to drain the water in excess. Therefore, to measure the severity of the risk factor the following financial KPI has been identified: "Percentage change in maintenance costs".

g) Setting of materiality thresholds (Risk appetite):

The farm's management is willing to absorb percentage increases in maintenance costs of up to 300%. Cost increases exceeding 300% represent critical deviations that can cause serious consequences for the firm's continuity. Therefore, the materiality threshold is set at a percentage change in maintenance costs equal to +300%, representing the firm's risk appetite.

h) Quantification of the effect (Severity function):

As in the previous cases, the estimate of the severity function is based on expert judgment collected through the KnowShape platform. The result is as follows:

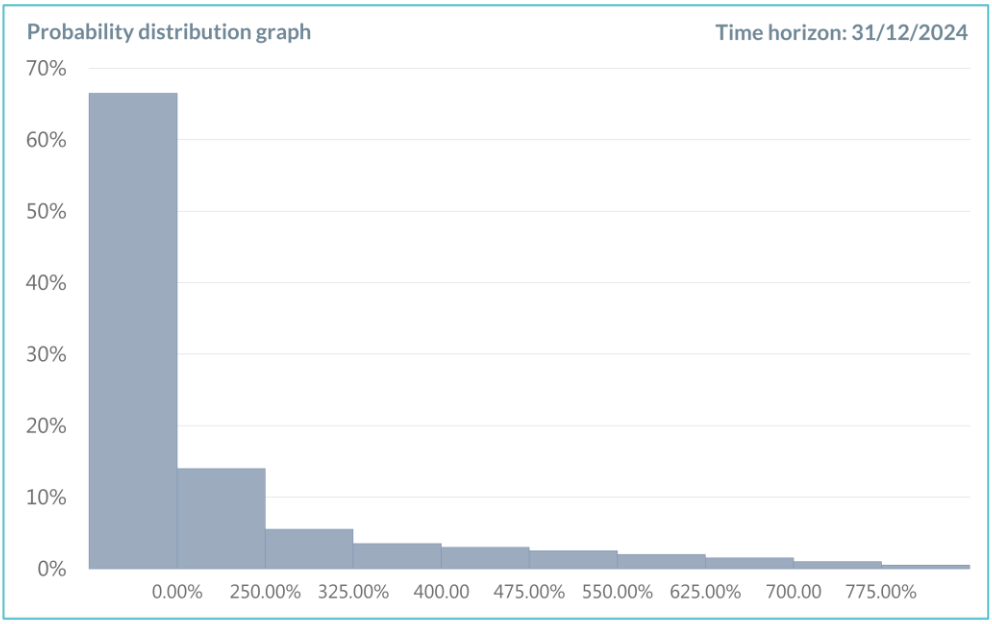
- Less than 120 mm weekly rainfall:
  - Percentage change in maintenance costs = 0%.
  - Motivations: no farmland maintenance interventions are necessary as, at these levels of rainfall, the composition of the soil guarantees correct drainage.
- Weekly rainfall between 120 and 150 mm:
  - Percentage change in maintenance costs = +250% (mean value of the effects related to the interval of risk factor intensities).
  - Motivations: it would be difficult for the soil to rapidly drain the water in excess. Some products (mainly the Dorona grapevine) would be at risk of root asphyxiation. In this case land maintenance operations would be necessary in order to drain the water in excess, with an estimated percentage increase in maintenance costs of 250%.
- More than 150 mm weekly rainfall:
  - Percentage change in maintenance costs = +600% (mean value of the effects related to the interval of risk factor intensities)
  - Motivations: such high levels of rain precipitation would cause root asphyxiation to grapevines, thus damaging production. Furthermore, land maintenance operations would be necessary in order to drain the water in excess, leading other more resistant crops to rotting. The estimated percentage increase in maintenance costs is of 600%.

Again, this estimate of the severity function satisfies the full range requirements on severity (for the possible different intensities of the risk factor) that are required by ESRS 1.

i) Estimate of the effect indicator probability distribution (Financial KPI distribution):

The estimate represented in the figure below is a necessary step to calculate the probability that financial KPI values greater than the identified materiality threshold will occur[30]. In line with the estimated probability distribution for the risk factor, most likely (with 65% probability) there will be no financial impacts. However, by looking at the full range of possible outcomes, one realizes that the probability of a cost increase is non-negligible.

[30] The severity probability distribution was calculated using the KnowShape platform feeded by the risk factor distribution (point d) and the severity function (point h)



j) Judgment on materiality:

With a time horizon until 31/12/2024, the probability of observing percentage changes in maintenance costs exceeding 300% (materiality threshold) obtained from the severity distribution is very significant and equal to 20%. The increase in maintenance costs equal to 300% occurs for weekly rainfall greater than 120 mm but lower than 150 mm. The risk factor is therefore material and adaptation solutions must be defined to mitigate its prospective impacts.

k) If the effect is assessed as material, development of the related action plan (Adaptation plan to physical risk):

The adaptation solution identified is a soil drainage system aimed at protecting fields from flooding. This system includes a network of pipes and channels that efficiently drain excess water from the fields. The system is designed to activate when the cumulative weekly rainfall exceeds 120 mm. In this way, no farmland maintenance interventions are necessary as the drainage system will guarantee the correct drainage of the soil and therefore there will be no percentage increases in maintenance costs.

4.4 Case 4: acute risk [Flood – coastal]

STEP 1: Analysis of the cause

a) Definition of future time horizon:

The risk of exceptional high tides is mapped with the "Flood - coastal" regulatory risk factor. Exceptional high tides are an acute physical risk factor. Acute physical risks arise from short-term extreme weather events; for this reason, the "Flood - coastal " risk factor is assessed over a short horizon (1 year), with reference to 31/12/2024.

b) Identification of the cause indicator (Physical risk factor):

In order to measure the "Flood - coastal" risk factor, the following risk factor indicator has been identified: "monthly maximum tide". This indicator is suitable for the following two reasons: i) the maximum tide represents the extreme event that can affect firm's continuity; ii) the use of the monthly frequency allows to consider the seasonal dynamics of the extreme events.

c) Collection of information on the cause indicator and projections:

The following public scientific data have been collected for the "monthly maximum tide":

- Tide (cm) (tide instant measurements). Values are measured with reference to the ZMPS.
- Source: ISPRA.

For details on data see Appendix 6.4.

The "Flood - coastal" risk factor is an acute risk factor. Also in this case, one needs to analyse extreme peaks, which are particularly harmful, as well as heteroskedasticity (dynamic volatility) in order not to underestimate the extreme tails. We perform these analyses by applying univariate dynamic statistical models to high resolution data.

The result is as follows:

- Statistical model specification for projecting the monthly maximum tide:

$$HighTide_t = 70.065 + 0.025Trend + 0.150HighTide_{t-1} + 16.417\mathbb{D}_{10} + 22.256\mathbb{D}_{11} + 16.875\mathbb{D}_{12} + \varepsilon_t$$

  Where $\mathbb{D}_{10}$, $\mathbb{D}_{11}$, e $\mathbb{D}_{12}$ are the dummy variables for the months of October, November and December respectively.

  The results of the model specification are fully reported in Appendix 6.4.

- Statistical model's projections over the horizon until 31/12/2024 for the monthly maximum tide:

$$MIN = 50\ cm$$

$$MODE = 82.78\ cm$$

$$MAX = 189\ cm$$

  Where:

  MIN = Time series minimum value.

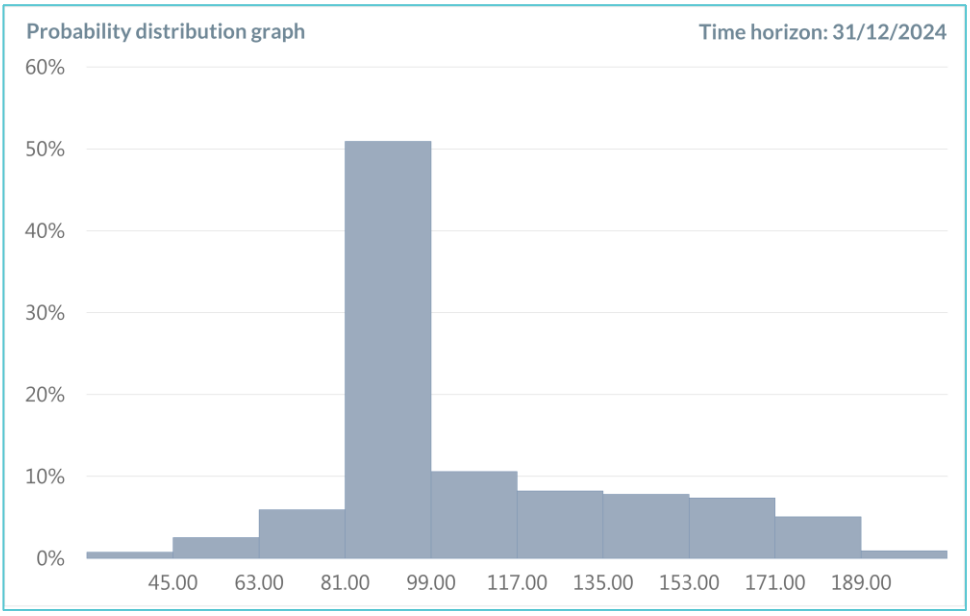
  $MODE$ = Model's expected value.

  MAX = Time series maximum value.

  Since the "Flood - coastal" risk factor is an acute risk factor, it is necessary not to underestimate its extreme peaks. Therefore, for the statistical projections of the minimum (MIN) and maximum (MAX) values, the time series minimum and maximum values have been used.

d) Estimate of the cause indicator probability distribution:

The estimate of the distribution, based on the hypothesis-free approach from KnowShape, is represented in the figure below. The most likely outcome, with around 50% probability, is that the monthly maximum tide will be between 81 and 99 cm.



e) Consistency check on the estimated probability distribution:

The projection of the minimum value (point c) is equal to 50 cm, and the distribution (point d) highlights a residual probability for values lower than 50 cm. The projection of the maximum value is equal to 189 cm, and the distribution highlights a residual probability for values greater than 189 cm. Finally, the projection of the modal value is equal to 82.78 cm, while the distribution has a modal range between 81 cm and 99 cm. Hence, the projections and the estimated probability distribution are consistent.

STEP 2: Analysis of the effect

f) Identification of the effect indicator (Financial KPI):

Extreme high tide events could erode the island's banks and increase the salinity of cultivated land. In these cases, the morphological restoration of the island would be necessary. Therefore, in order to measure the severity of the risk factor, the following financial KPI has been identified: "Costs for morphological restoration".

g) Setting of materiality thresholds (Risk appetite):

The farm's management is willing to sustain costs for morphological restoration of up to +120% of annual production costs. Greater costs for morphological restoration represent critical deviations that can cause serious consequences for the business continuity of the firm itself. Therefore, the materiality threshold is set at costs for morphological restoration of up to +120% of annual production costs, representing the firm's risk appetite.

h) Quantification of the effect (Severity function):

We use the KnowShape platform owing to its collection of structured expert judgment to estimate the severity function. The result is as follows:

- For all intensities of the risk factor:
  - Costs for morphological restoration = 0.
  - Motivations: on the basis of the scientific data and in relation to the time horizon 31/12/2024, a tide of 189 cm is the worst-case scenario. This event has already occurred during the Acqua Granda in November 2019, seriously damaging the island. However, since 2020 a series of barriers consisting of mobile gates located at the lagoon inlets (so-called MOSE) protects Venice and the lagoon from tides up to 3 meters high[31]. It can therefore be concluded that thanks to the MOSE, the island is protected from the impacts of the "exceptional high tides" risk factor. The estimate of the severity function is therefore equal to zero for all intensities of the risk factor.

i) <u>Estimate of the effect indicator probability distribution (Financial KPI distribution):</u>

Given that thanks to the MOSE the costs for morphological restoration are zero for all intensities of the risk factor, the severity distribution is entirely concentrated on the value 0.

j) <u>Judgment on materiality (Financial materiality of physical risk factor):</u>

Since the financial KPI is always below the materiality threshold, the risk factor is assessed as non-material.

k) <u>If the effect is assessed as material, development of the related action plan (Adaptation plan to physical risk):</u>

Given that the risk factor is assessed as non-material, it is not necessary to formulate an action plan.

[31] Source: Consorzio Venezia Nuova (*www.mosevenezia.eu*).

5. Conclusions

Against an increasingly demanding regulatory environment, companies need rigorous guidance and tools on how to implement the quantitative double materiality assessment in full compliance with regulatory requirements. While regulators cannot provide practical guidance applicable to all firms, given the specificity of their businesses, science has a role to play by offering examples where the double materiality assessment is carried out in a quantitative and rigorous manner.

In this paper, we have developed the first attempt to a quantitative financial materiality assessment following relevant regulatory requirements. The proposed approach only uses publicly available data on physical risk factors and is fully transparent on the underlying assumptions and calculations. On data availability, in our case very detailed geolocalized data on relevant indicators (such as temperature and sea level) were easily obtained from the relevant regional authority. In other cases, relevant data are provided by national authorities. It is also possible to resort to natural hazard maps for the EU as a whole, such as those provided by the Joint Research Centre of the European Commission through its Risk Data Hub[32]. Although market solutions exist, which associate firms to levels of physical risks for various hazards, we recommend using publicly available data, to be sure and transparent about e.g. the underlying climate warming scenarios and the level of granularity of the estimates.

Moving to the estimation of financial effects, the proposed approach leverages expert judgment (of firm managers and/or advisors) in order to consider the significant idiosyncratic features of the severity function. The involvement of the firm's management, on top of being necessary for the derivation of the severity function and the identification of the materiality threshold, contributes to raise awareness at management level about the relevance of ESG risks.

Finally, we have focussed on climate physical risk, owing to its universal relevance and the attention that regulators and supervisors are paying to it. However, the methodology presented could be in principle adjusted and extended to other risks, belonging to the environmental dimension and beyond. For example, in the case of a production process involving the use of water, one could use indicators of water pollution as cause indicators, project their values over the relevant horizon, establish impacts based on available scientific literature and technical knowledge (in particular about the threshold levels beyond which water becomes too polluted to be usable for production), and perform the associated financial effects analysis. The approach used in this paper could be used also by financial institutions. For example, banks' financial materiality assessment could be carried out rather straightforwardly by applying the methodology to loan portfolios, which would involve the estimation of relevant probabilities of default of banks' counterparts. Regarding social and governance matters, depending on the complexity of the issues, the analysis could be characterized by varying degrees of complexity. In particular, it could be arguably more difficult to perform a financial materiality assessment related to a particular social or governance matter, compared to an assessment related to physical risks, as there may be more than one relevant cause indicator for a given social or governance factor (possibly quite different from each other), several financial indicators could be impacted, and it might not be straightforward to derive a severity function. Further research in this direction is warranted to provide companies with blueprints.

[32] www.drmkc.jrc.ec.europa.eu/risk-data-hub.

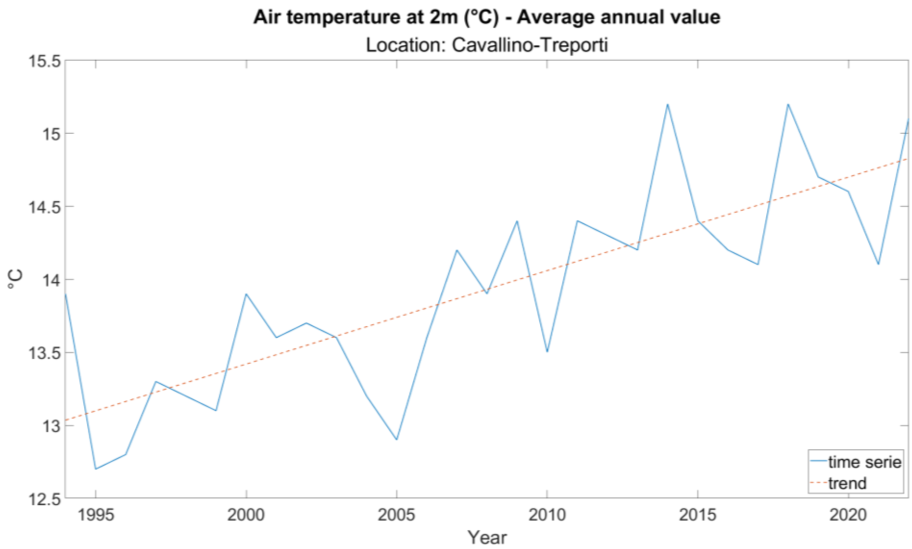
6. Appendix – statistical analysis

6.1 Case 1: chronic material risk [Changing temperature – air]

6.1.1 Data source

Source	ARPAV
Data	Air temperature at 2m (°C) - average annual value
Link to data	https://www.arpa.veneto.it/dati-ambientali/open-data/clima/principali-variabili-meteorologiche
Location	Cavallino-Treporti
Sample period	1994 - 2022
Notes	(1) The annual average value is the average value of the monthly values which are calculated on the daily averages of the relative month. (2) The temperature measurement is carried out with thermometers positioned 2 meters from the ground. (3) Data from the ARPAV station of Cavallino-Treporti were used as it is the closest to the island (the other ARPAV stations are in Venice - Istituto Cavanis, Jesolo - Cortellazzo and Marcon while the closest ISPRA station is located at Lido of Venice). (4) ARPAV is the Regional Agency for Environmental Protection (ARPA) of the Veneto region. Like all ARPAs, it is subject to direction and coordination by ISPRA (Italian Higher Institute for Environmental Protection and Research). Therefore, the quality of the data is very high and certified.

6.1.2 Graphic analysis



As can be seen from the graph, the average annual air temperature in the Cavallino-Treporti area follows an increasing trend. The hypothesis is that the stochastic process underlying the average annual air temperature is trend stationary.

6.1.3 Stationarity analysis

1. The Augmented Dickey-Fuller (ADF) test with trend-stationary alternative gave the following outcome:

Rejection decision	1
p-Value	1.0000e-03
Test statistic	-5.9006

   The outcome of the test leads to reject the null hypothesis H_0 that the process is non-stationary with unit root in favour of the alternative hypothesis H_1 that the process is trend stationary.

2. The Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test gave the following outcome:

Rejection decision	0
p-Value	0.1000
Test statistic	0.0465

   The outcome of the test leads to not reject the null hypothesis H_0 that the process is trend stationary.

The outcomes of the ADF and KPSS tests confirm the initial hypothesis that the process is trend stationary.

6.1.4 Model specification

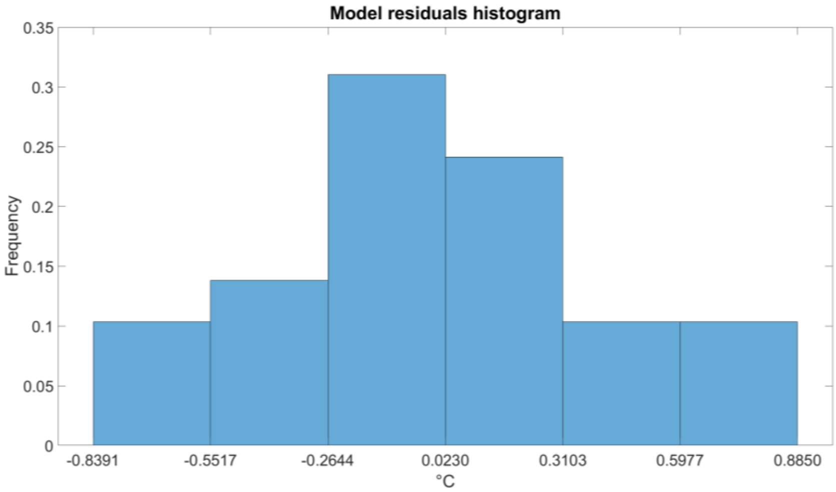
```
Estimated Coefficients:
                   Estimate        SE         tStat       pValue
                   ________    _________    ______    __________

    (Intercept)    -114.56        19.121    -5.9915    2.1638e-06
    Year           0.06399     0.0095222     6.7201    3.2499e-07


Number of observations: 29, Error degrees of freedom: 27
Root Mean Squared Error: 0.429
R-squared: 0.626,  Adjusted R-Squared: 0.612
F-statistic vs. constant model: 45.2, p-value = 3.25e-07
```

From which the following specification of the model is obtained:

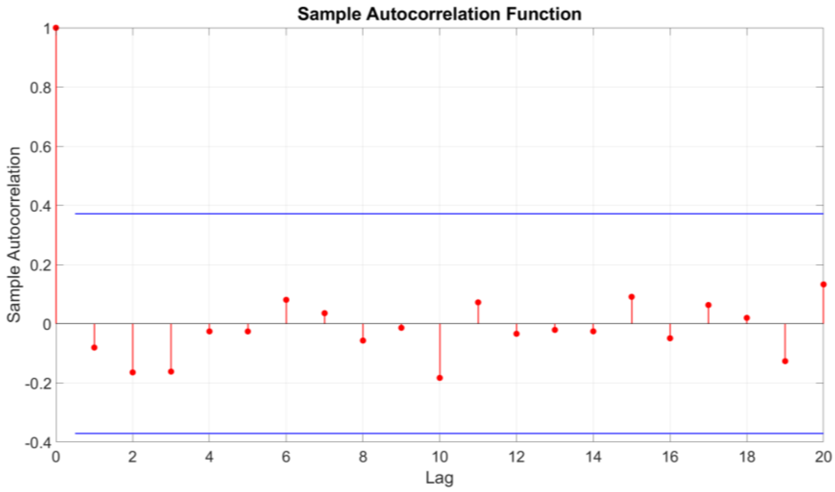
$$AirTemp_t = -114.56 + 0.06399 Year_t + \varepsilon_t$$

6.1.5 *Residual analysis*

1. Residuals histogram:



2. Residuals correlogram:



As the time lag varies, the autocorrelation coefficients of the residuals are all within the confidence band, this indicates the absence of autocorrelation.

3. The Ljung-Box Q-test for verifying the autocorrelation of the residuals gave the following outcome:

Rejection decision	0
p-Value	0.9858
Test statistic	8.7324

The outcome of the test leads to not reject the null hypothesis H_0 that the residuals are not autocorrelated.

4. The ARCH-test for verifying the homoscedasticity of the residuals gave the following outcome:

Rejection decision	0
p-Value	0.4375
Test statistic	0.6027

The outcome of the test leads to not reject the null hypothesis H_0 that the series of the residuals does not shows the presence of conditional heteroskedasticity (homoscedastic residuals).

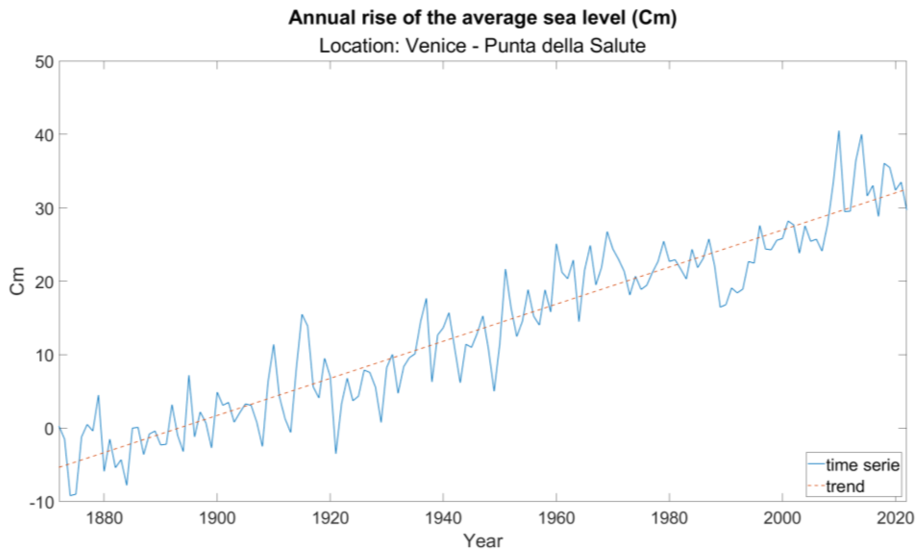
The outcome of the two tests on the regression residuals leads to confirm that the residuals are not autocorrelated and are homoscedastic.

6.2 Case 2: chronic non material risk [Sea level rise]

6.2.1 Data source

Source	ISPRA
Data	Annual rise of the average sea level (cm). Referred to the hydrographic zero of Punta della Salute (ZMPS)
Link to data	https://indicatoriambientali.isprambiente.it/it/laguna-di-venezia/crescita-del-livello-medio-del-mare-venezia-iclmm
Location	Venice - Punta della Salute
Sample period	1872 - 2022
Notes	(1) The indicator summarizes well the trend of the average sea level in the long term. The data comes from the same station (Punta della Salute); therefore, the comparability is excellent. The Punta della Salute station was managed by the Ufficio Idrografico del Magistrato alle Acque, subsequently by APAT and finally by ISPRA. The procedures for examining, validating and archiving the data have been maintained over time. Furthermore, during 2015 the validation process of the RMLV tidal data was included in the ISPRA UNI EN ISO 9001:2015 certification domain. Reliability is excellent. The spatial coverage is limited to the historic centre of Venice, although it can be taken as a reference for the entire Venice Lagoon, by virtue of its central position. The calculation methodology is valid in time and space. (2) Since the entry into force of the MOSE system in 2020 the average sea level of Punta della Salute has been calculated with two different methodologies: Methodology a) it is the average of the sea levels recorded inside the historical centre of Venice during the year (Punta della Salute station), including the values measured during the MOSE activation. Methodology b) the sea level of Punta della Salute is integrated, only on the days when the MOSE is activated, with the average daily sea level recorded at Piattaforma Acqua Alta, a station located about 8 nautical miles off the coast in front of Venice. This methodology guarantees the continuity of the 100 year-historical series of Punta della Salute as the daily value recorded at Piattaforma Acqua Alta is comparable and consistent with what would have been recorded in the lagoon without the MOSE activation; the sea levels as well as those inside the lagoon are in fact referred commonly to the ZMPS. In the statistical analyses reported in this paper, for average sea level data after 2020, the data calculated with methodology b are used. In this way, the series does not present structural breaks due to the intervention of the MOSE system.

6.2.2 Graphic analysis



As can be seen from the graph, the annual growth of the average sea level recorded in the Venice - Punta della Salute area follows an increasing trend. The hypothesis is that the stochastic process underlying the average annual air temperature is trend stationary.

6.2.3 Stationarity analysis

1. The Augmented Dickey-Fuller (ADF) test with trend-stationary alternative gave the following outcome:

Rejection decision	1
p-Value	1.0000e-03
Test statistic	-8.6874

   The outcome of the test leads to reject the null hypothesis H_0 that the process is non-stationary with unit root in favour of the alternative hypothesis H_1 that the process is trend stationary.

2. The Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test gave the following outcome:

Rejection decision	0
p-Value	0.0820
Test statistic	0.1287

   The outcome of the test leads to not reject the null hypothesis H_0 that the process is trend stationary.

The outcomes of the ADF and KPSS tests confirm the initial hypothesis that the process is trend stationary.

6.2.4 Model specification

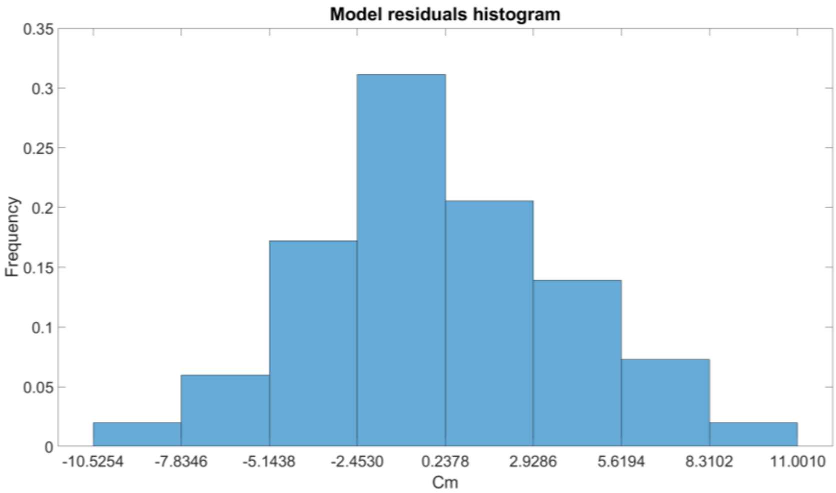
```
Estimated Coefficients:
                   Estimate        SE          tStat       pValue
                   ________    _________     ________    __________

    (Intercept)    -478.27        14.225     -33.622     1.8611e-71
    Year           0.25262     0.0073041      34.587     4.4304e-73


Number of observations: 151, Error degrees of freedom: 149
Root Mean Squared Error: 3.91
R-squared: 0.889,  Adjusted R-Squared: 0.888
F-statistic vs. constant model: 1.2e+03, p-value = 4.43e-73
```

From which the following specification of the model is obtained:

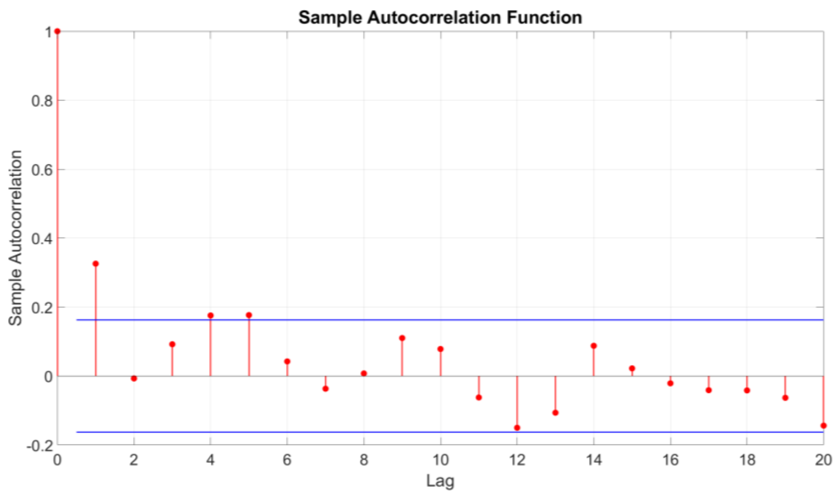
$$SeaLevel_t = -478.27 + 0.25262 Year_t + \varepsilon_t$$

6.2.5 Residuals analysis

1. Residuals histogram:



2. Residuals correlogram:



With regards to lags 1, 4 and 5, the autocorrelation coefficients of the residuals are outside the confidence bands, therefore indicating the presence of autocorrelation.

3. The Ljung-Box Q-test for verifying the autocorrelation of the residuals gave the following outcome:

Rejection decision	1
p-Value	0.0017
Test statistic	43.6515

The outcome of the test leads to reject the null hypothesis H_0 in favour of the alternative hypothesis H_1 that the residuals are autocorrelated.

4. The ARCH-test for verifying the homoscedasticity of the residuals gave the following outcome:

Rejection decision	0
p-Value	0.3414
Test statistic	0.9053

The outcome of the test leads to not reject the null hypothesis H_0 that the series of the residuals does not shows the presence of conditional heteroskedasticity (homoscedastic residuals).

The outcome of the two tests on the regression residuals leads to confirm that the residuals are autocorrelated and homoscedastic.

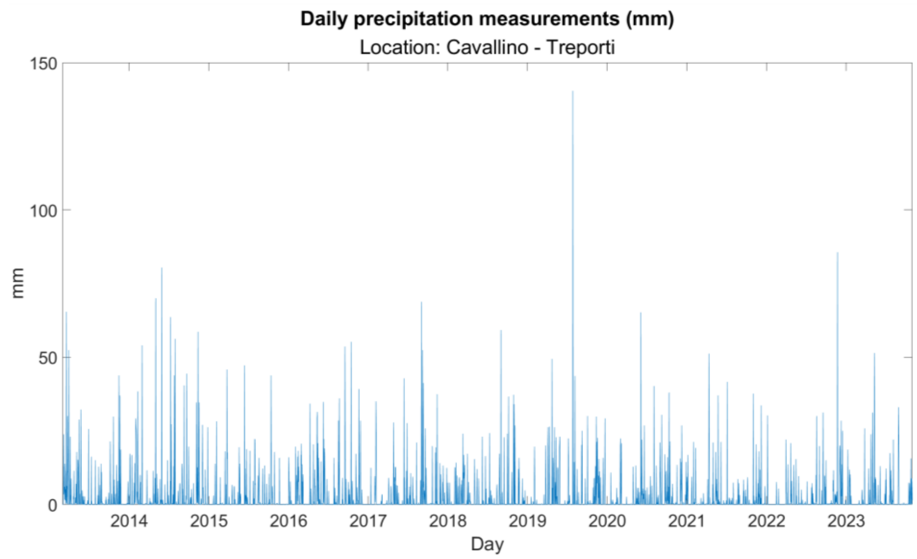
As a chronic physical risk factor, the "Sea level rise" risk factor is assessed over the long-term. Hence, we need to focus on the trend component of the stochastic process that describes the observations on this risk factor. To this end, the residuals' autocorrelation doesn't affect the trend component analysis.

6.3 Case 3: acute material risk [Heavy precipitation – rain]

6.3.1 Data source

Source	ARPAV
Data	Daily precipitation measurements (mm)
Link to data	https://www.arpa.veneto.it/dati-ambientali/dati-storici/meteo-idro-nivo/ultimi_anni
Location	Cavallino-Treporti
Sample period	2010-2023
Notes	(1) Data from the ARPAV station of Cavallino-Treporti were used as it is the closest to the island (the other ARPAV stations are in Venice - Istituto Cavanis, Jesolo - Cortellazzo and Marcon while the closest ISPRA station is located at Lido of Venice). (2) ARPAV is the Regional Agency for Environmental Protection (ARPA) of the Veneto region. Like all ARPAs, it is subject to direction and coordination by ISPRA (Italian Higher Institute for Environmental Protection and Research). Therefore, the quality of the data is very high and certified.

6.3.2 Graphic analysis



Daily rainfall cannot be used directly as an indicator of the "Heavy rain" risk factor as it presents two different problems:

a) Analysing the amount of water rained in a single day is not sufficient to assess the "severity" of the "Heavy rain" event. In fact, the severity of the precipitation phenomenon is linked not only to the amount of water rained in a single day but also if in the previous or subsequent days precipitation phenomena occurred such as to aggravate the situation (flooding of crops on the island).

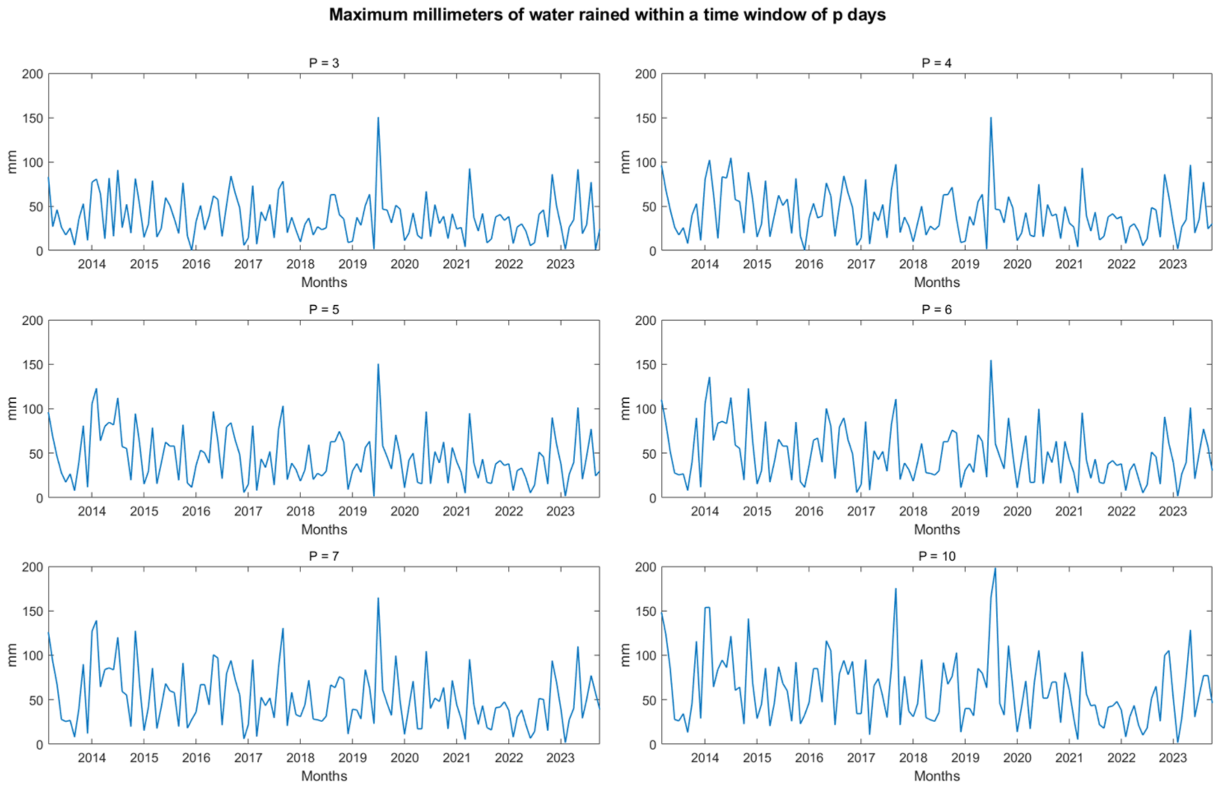
b) Daily frequency data are not suitable to clearly identify the presence of seasonality of extreme events.

In order to address the problems described above, the maximum millimetres of water rained within a time window of p days for each month of the sample has been calculated, so as to construct a monthly series of extreme precipitation events. The use of time windows allows to consider the temporal persistence of the precipitation phenomenon (thereby solving the first problem) while the monthly frequency of the series allows to better highlight any seasonal dynamics (therefore solving the second problem).

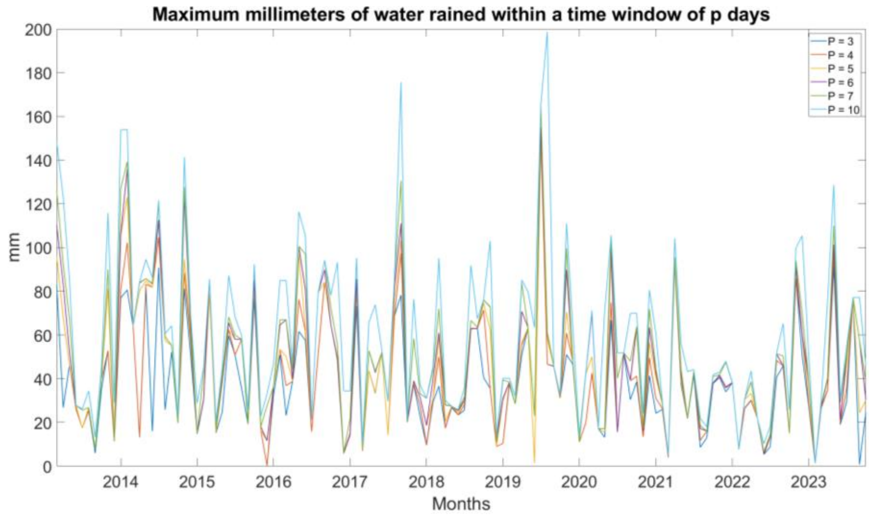
When constructing the risk factor indicator, the number of days p to be used must be selected.

To this end, 6 different time series were calculated by differentiating the length of the time windows of p days: $p = [3,4,5,6,7,10]$.

Below are the graphs of the outcomes:



To compare the outcomes, the merged graph of all the calculated series is analysed below:

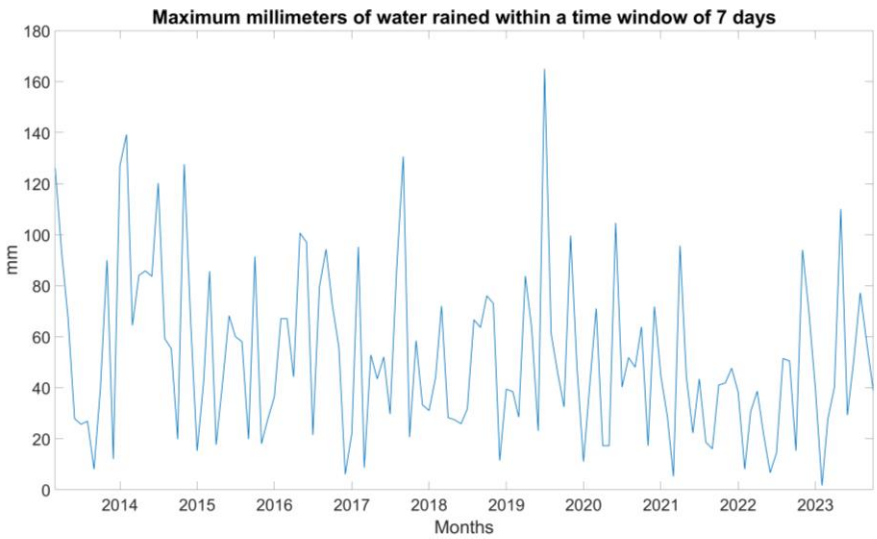


From the comparison of the time series, a significant correlation between them is identified. This means that the identification of the extreme precipitation event is independent from the number of days used for the time window. The estimate of the correlations between the 6 calculated series is reported in the table below:

	P3	**P4**	**P5**	**P6**	**P7**	**P10**
P3	1	0.946245	0.904438	0.874677	0.867602	0.769844
P4	0.946245	1	0.954921	0.936125	0.92762	0.827497
P5	0.904438	0.954921	1	0.982117	0.96992	0.87184
P6	0.874677	0.936125	0.982117	1	0.988169	0.89868
P7	0.867602	0.92762	0.96992	0.988169	1	0.914837
P10	0.769844	0.827497	0.87184	0.89868	0.914837	1

The outcomes shows that the identification of extreme precipitation phenomena is sufficiently independent with respect to the selection of the size of the time window. Therefore, the time series constructed with the number of days $p = 7$ has been selected as the risk factor's indicator. The reason for choosing 7 days is that using a week as a time reference represents a standard measurement that is easy to understand.

The graph of the time series with a number of days equal to 7 is reported below:



6.3.3 Stationarity analysis

The Augmented Dickey-Fuller (ADF) test with autoregressive alternative gave the following outcome:

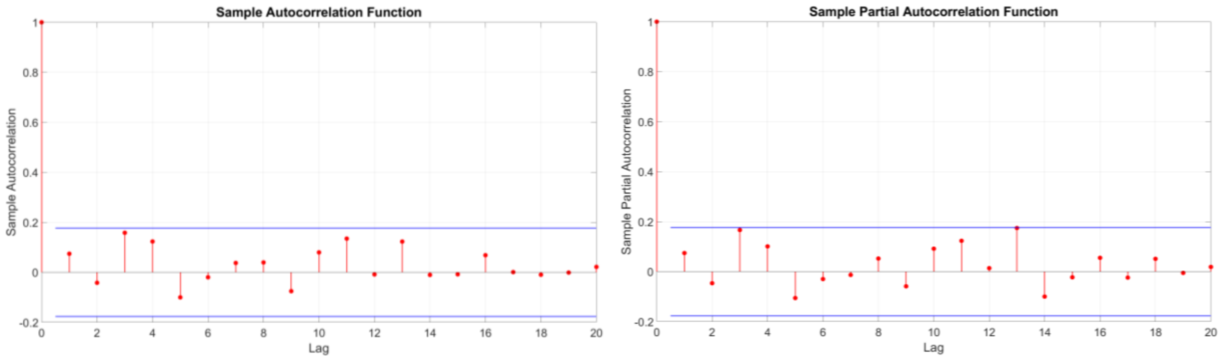
Rejection decision	1
p-Value	1.0000e-03
Test statistic	-4.6044

The outcome of the test leads to reject the null hypothesis H_0 that the process is non-stationary with unit root in favour of the alternative hypothesis H_1 that the process is stationary.

6.3.4 Model specification

As an acute physical risk factor, the "Heavy precipitation - rain" risk factor is assessed over the short-term. Hence, we need to focus on short-run dynamics of the stochastic process that describes the observations on this risk factor. To this end, the autocorrelation analysis plays a crucial role.

The series at levels is stationary, therefore an $AR(p)$ model is to be specified. The analysis of the correlograms of the series is performed to choose the order p.



As can be seen from the analysis of the correlograms, the autocorrelation coefficients are all within the confidence band, this indicates the absence of autocorrelation. The partial autocorrelation coefficients are also all within the confidence bands. Therefore an $AR(0)$ model is specified.

The model's estimation gave the following outcomes:

Parameter	Value	Standard Error	t Statistic	P-Value
Constant	52.0656	3.4861	14.9353	1.9408e-50
Variance	1081.2361	147.5991	7.3255	2.3802e-13

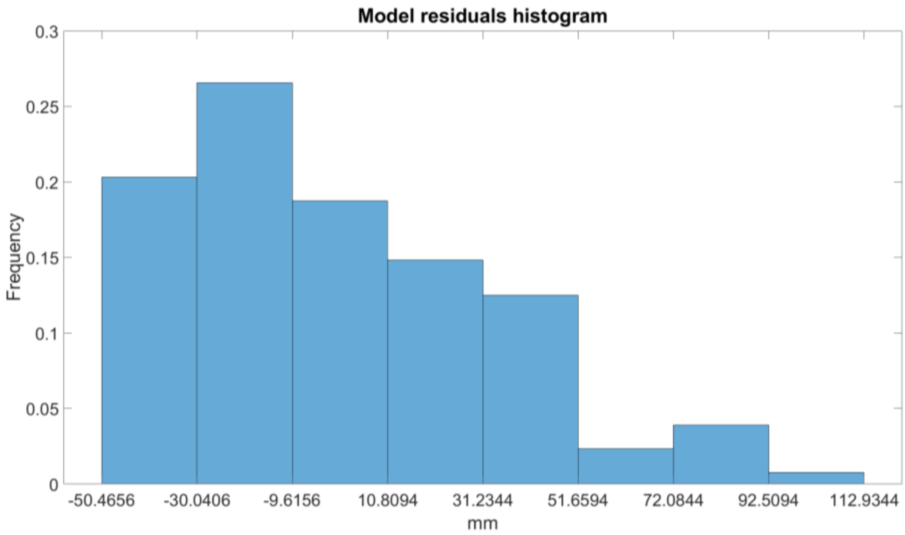
AIC	1260.4384
BIC	1266.1425

From which the following specification of the model is obtained:

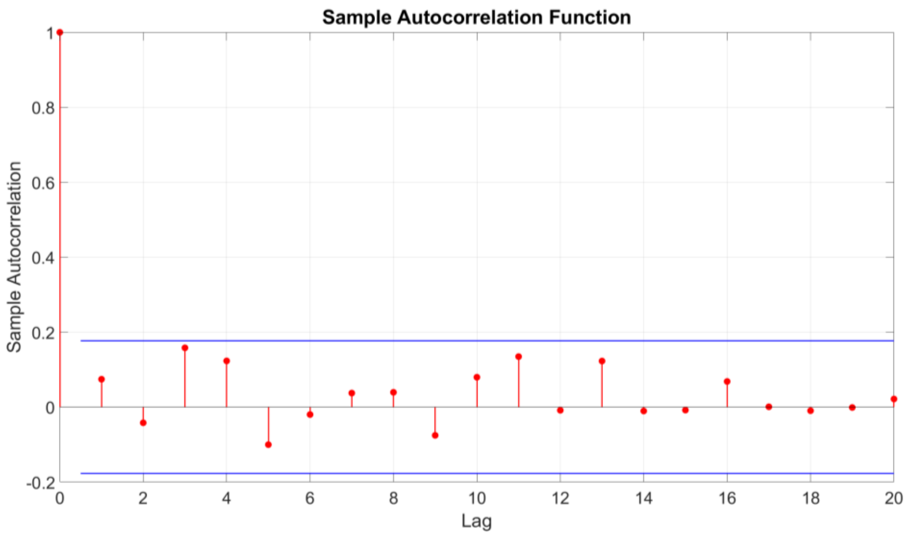
$$HeavyRain_t = 52.0656 + \varepsilon_t$$

6.3.5 *Residuals analysis*

1. Residuals histogram:



2. Residuals correlogram:



As the time lag varies, the autocorrelation coefficients of the residuals are all within the confidence band, this indicates the absence of autocorrelation.

3. The Ljung-Box Q-test for verifying the autocorrelation of the residuals gave the following outcome:

Rejection decision	0
p-Value	0.75212
Test statistic	15.4161

The outcome of the test leads to not reject the null hypothesis H_0 that the residuals are not autocorrelated.

4. The ARCH-test for verifying the homoscedasticity of the residuals gave the following outcome:

Rejection decision	0
p-Value	0.50182
Test statistic	0.45108

The outcome of the test leads to not reject the null hypothesis H_0 that the series of the residuals does not shows the presence of conditional heteroskedasticity (homoscedastic residuals).

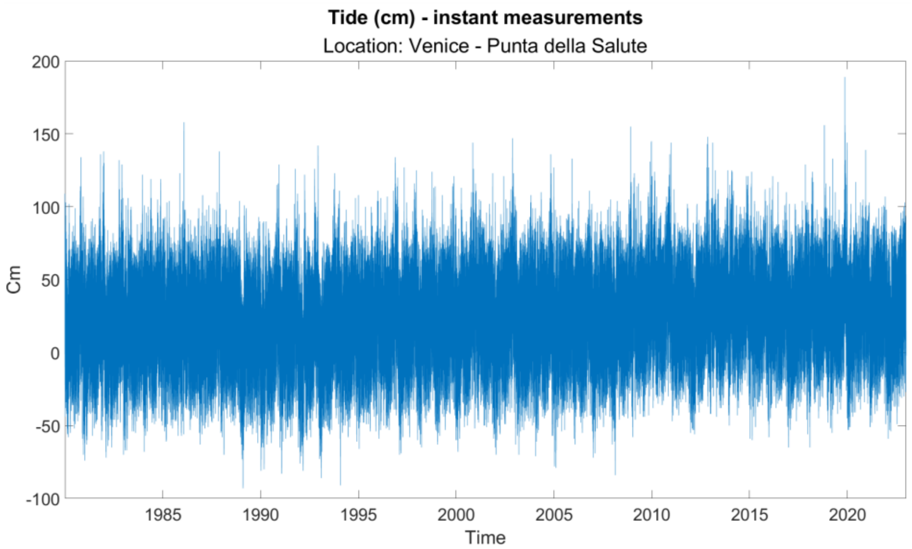
The outcome of the two tests on the regression residuals leads to confirm that the residuals are not autocorrelated and are homoscedastic.

6.4 Case 4: acute non-material risk [Flood – coastal]

6.4.1 Data source

Source	ISPRA
Data	Tide (cm), instant measurements[33]. Values are measured with reference to the ZMPS.
Link to data	https://www.venezia.isprambiente.it/index.php?folder_id=20&stazione_id=129&tipo_dati_id=1&view=year
Location	Venice - Punta della Salute
Sample period	1980-2022
Notes	Data collected by Punta della Salute station were selected as they are the data commonly looked at for activities in the historical centre of Venice. Data collected in the Burano station (that is closest to the island and managed by the Rete Mareografica del Comune di Venezia CPSM) are also available. However, the data from the Burano station present some issues: the maximum value recorded was 1.55 cm on 01/12/2008. Certainly, during the *Acqua Granda* of 12/11/2019 the tide value was higher but in the Burano database it is recorded as 1.53 cm at 11pm. Furthermore, considering the high presence of empty values, Burano station data are not considered reliable. Therefore, the data collected by Punta della Salute station were used.

6.4.2 Graphic analysis



Instant tide measurements cannot be used directly as an indicator of the "Flood - coastal" risk factor as they do not allow to highlight seasonal dynamics. Furthermore, it is important to analyse the series

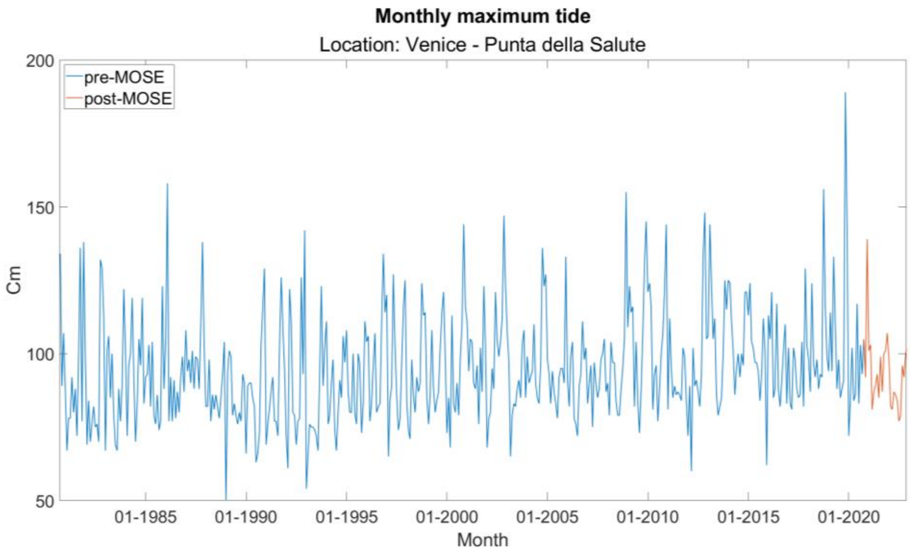
[33] "Instant measurements" means the data at the highest available frequency at the time of the recording. The highest available frequency has increased over the years, from 4 daily recordings in the early 1980s to one recording every 10 minutes (2007 to present).

by dividing it into two subsamples: the tidal data prior to the entry into operation of the MOSE (until September 2020) and the subsequent data. In fact, to model high tides in relation to locations inside the Venice lagoon, reference must only be made to data prior to the entry into operation of the MOSE (subsequent data are distorted by its functioning).

To address these issues, the sample period has been divided into two subsamples: pre-MOSE (10/1980 – 09/2020) and post-MOSE (10/2020 – 12/2022). Subsequently, the two time series relating to the pre-MOSE and post-MOSE monthly maximum tide were obtained.

The data thus obtained allow to address the aforementioned issues: firstly, using a monthly frequency allows to highlight the seasonal dynamics of extreme events; secondly, the risk factor analysis will be carried out on the pre-MOSE series, isolating the dynamics of the physical phenomenon without the structural break generated by the MOSE intervention.

The graph of the data is reported below:



To analyse the effectiveness of the MOSE system, the extreme peaks that occurred before and after the introduction of the MOSE must be analysed. As can be seen, following the introduction of the MOSE, tides higher than 140 cm have no longer occurred[34]. Only on 8 December 2020 an exceptional tide event occurred with a tide of 139 cm. On that day the MOSE was not activated because a maximum tide peak of 125 cm was forecasted and the MOSE activation procedure that was in force allowed the lifting of the bulkheads with forecast tides higher than 130 cm[35].

After the event of 8 December 2020, the lifting procedures became progressively more stringent and exceptional tide events no longer occurred inside the lagoon. From the 2024-2025 season, the MOSE is expected to be lifted with maximum tide forecasts equal to or greater than 110 cm, reaching the maximum level of protection envisaged by the project[36].

[34] The threshold of 140cm is used by the Municipality of Venice to identify exceptional high tides. See the following link: *https://www.comune.venezia.it/it/content/le-acque-alte-eccezionali*

[35] Municipality of Venice: *https://www.comune.venezia.it/it/content/acqua-alta-mercoled-2-dicembre-alle-1045-prevista-una-marea-125-130-cm*

[36] Italian Ministry of Infrastructure and Transport: *https://www.mit.gov.it/index.php/documentazione/sistema-mose-edilizia-statale*

6.4.3 *Stationarity analysis*

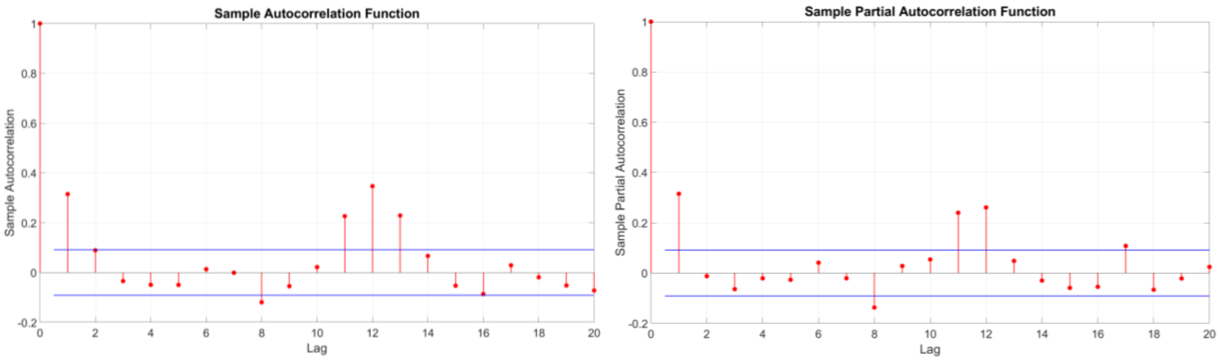
The Augmented Dickey-Fuller (ADF) test with trend-stationary alternative gave the following outcome:

Rejection decision	1
p-Value	0.0105
Test statistic	-2.5574

The outcome of the test leads to reject the null hypothesis H_0 that the process is non-stationary with unit root in favour of the alternative hypothesis H_1 that the process is stationary.

6.4.4 *Model specification*

As an acute physical risk factor, the "Monthly maximum tide" risk factor is assessed over the short-term time. Hence, we need to focus on short-run dynamics of the stochastic process that describes the observations on this risk factor. To this end, the autocorrelation analysis plays a crucial role.



From the analysis of the correlograms, a significant autocorrelation is observed at lag 1 and at lags 11,12,13. Therefore, it is assumed that the process is characterized by both an autoregressive and a seasonal dynamics.

On the basis of the analysis of the correlograms, the model was specified by inserting the following explanatory variables:

- The series lagged by one period to consider the autoregressive dynamics
- Monthly dummy variables to consider the seasonal dynamics
- The trend component to verify its significance

The model's estimation gave the following outcomes:

```
Estimated Coefficients:
                   Estimate        SE        tStat       pValue
                   ________    _________    ______    __________

    (Intercept)      70.065       3.9274     17.84    7.7321e-55
    y_L             0.14968     0.042779    3.4989    0.00051117
    D10              16.417       2.6011    6.3115    6.3542e-10
    D11              22.256       2.6677    8.3427    7.9869e-16
    D12              16.875       2.7673    6.0978    2.2333e-09
    trend          0.025046    0.0052913    4.7334    2.9194e-06


Number of observations: 480, Error degrees of freedom: 474
Root Mean Squared Error: 15.6
R-squared: 0.296,  Adjusted R-Squared: 0.289
F-statistic vs. constant model: 39.9, p-value = 3.28e-34
```

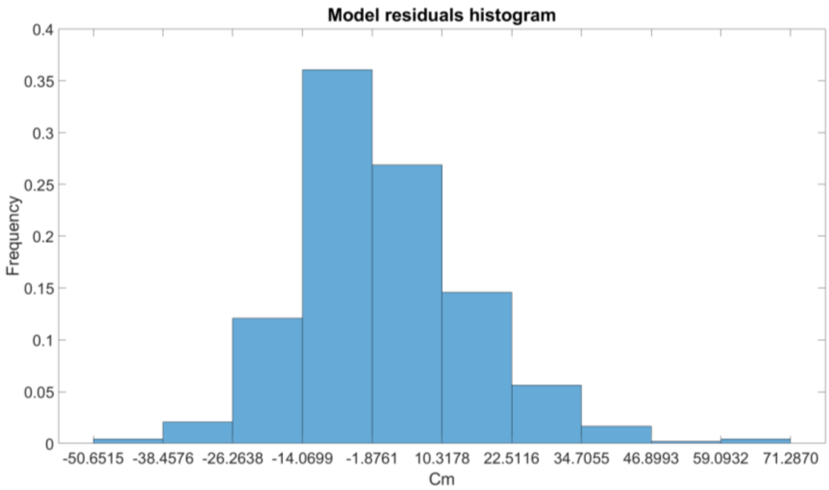
From which the following specification of the model is obtained:

$$HighTide_t = 70.065 + 0.025Trend + 0.150HighTide_{t-1} + 16.417\mathbb{D}_{10} + 22.256\mathbb{D}_{11} + 16.875\mathbb{D}_{12} + \varepsilon_t$$

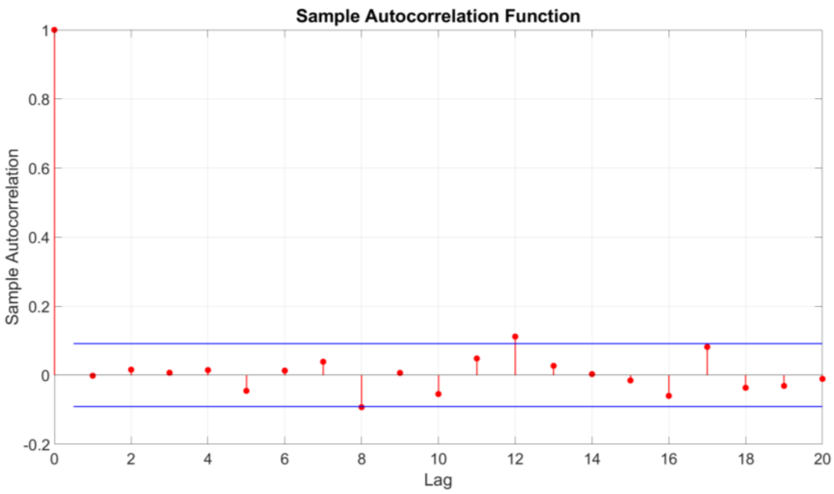
Where $\mathbb{D}_{10}$, $\mathbb{D}_{11}$, e $\mathbb{D}_{12}$ are the dummies variables for the months of October, November and December, respectively.

6.4.5 *Residuals analysis*

1. Residuals histogram:



2. Residuals correlogram:



As can be seen from the analysis of the correlogram, the autocorrelation coefficients of the residuals are all within the confidence bands with the exception of lag 12 which comes out slightly.

3. The Ljung-Box Q-test for verifying the autocorrelation of the residuals gave the following outcome:

Rejection decision	0
p-Value	0.3439
Test statistic	21.9381

The outcome of the test leads to not reject the null hypothesis H_0 that the residuals are not autocorrelated.

4. The ARCH-test for verifying the homoscedasticity of the residuals gave the following outcome:

Rejection decision	0
p-Value	0.0507
Test statistic	3.8183

The outcome of the test leads to not reject the null hypothesis H_0 that the series of the residuals does not shows the presence of conditional heteroskedasticity (homoscedastic residuals).

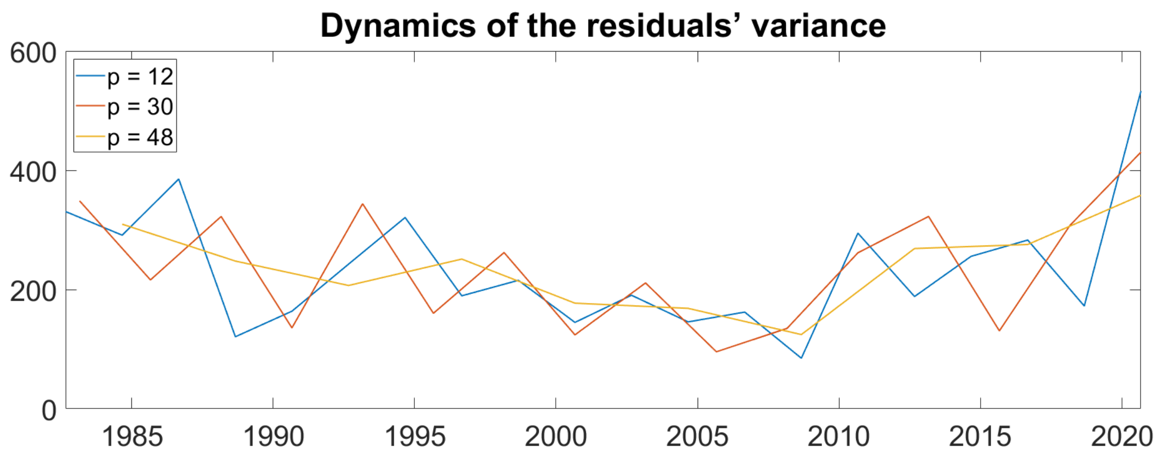
However, the pValue of the ARCH-test is just above the 5% confidence level. Therefore, to further investigate the presence of heteroscedasticity, the following analysis are performed:

a) Graphical analysis of the dynamics of the residuals' variance,

b) ARCH model on the series of the residuals,

a) Graphical analysis of the dynamics of the residuals' variance: three time series of the residuals' variance have been defined using time windows of different length p: 12 months, 30 months and 48 months.

The graph of these three time series showing the dynamics of the residuals' variance is reported below:



The graph clearly highlights that, in recent years, an increase in variance can be observed in all the three time series, with a significant peak around 2020. This peak is due to several extreme high tide events that occurred around that time, including the *Acqua Granda* occurred in

November 2019. This evidence deduced from the graphical analysis suggests the presence of heteroskedasticity on the residuals.

b) ARCH model on the series of the residuals: to delve deeper into the results obtained from the graphical analysis performed at the previous point a), the significance of the ARCH component on the residuals' series is analysed by estimating an $ARCH(1)$ model on the residuals' series. The outcomes are as follows:

	Value	StandardError	TStatistic	PValue
Constant	197.66	16.487	11.989	4.0676e-33
ARCH{1}	0.19198	0.062068	3.093	0.0019811

The outcomes show that the ARCH component is significant, confirming what was observed from the graphical analysis.

The analyses performed at points a) and b) suggest the presence of heteroscedasticity in the residuals. Given this evidence, the model specification reported in paragraph 6.4.4 could be improved by using a more complex analytical form through an ARCH model that considers the heteroscedasticity.

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