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Technical documentation of the risk-based UBA Air Quality Index

by:

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Kurzbeschreibung: Technische Dokumentation des risikobasierten UBA Luftqualitätsindex

Diese Dokumentation enthält die technische Beschreibung des überarbeiteten Luftqualitätsindex vom Umweltbundesamt. Der überarbeitete Luftqualitätsindex wurde als risikobasierter Ansatz entwickelt, der auf den neuesten Luftqualitätsleitlinien der Weltgesundheitsorganisation von 2021 fußt. Ein risikobasierter Index zielt darauf ab, das Risiko für Gesundheitseffekte von Schadstoffen in die Struktur und die Bewertung der Luftqualität des Index zu integrieren. Der hier vorliegende technische Bericht umfasst mehrere Teile, in denen das Konzept und die Schritte zur Erstellung des Index beschrieben werden.

Abstract: Technical documentation of the risk-based UBA Air Quality Index

This documentation contains the technical description of the revised air quality index of the German Environmental Agency. The revised air quality index was developed as a risk-based approach and is based on the latest World Health Organization Air Quality Guidelines published in 2021. A risk-based index aims to integrate the risk of health effects from pollutants into its structure and into the evaluation of air quality. The present technical report comprises several parts that describe the concept and the steps involved in creating the index.

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List of Abbreviations

Abkürzung	Erläuterung
APHENA-Studie	Air Pollution and Health: A Combined European and North American Approach
AQG	Global Air Quality Guidelines
AQI	Air Quality Index
BImSchV	Ordinance on the Implementation of the Federal Immission Control Act
COPD	Chronic obstructive pulmonary disease (Chronisch obstruktive Lungenerkrankung)
CVD	cardiovascular disease
EC	European Commission
EC Draft 2022	Directive of the EU Parliament and of the Council on ambient air quality and cleaner air for Europe 2022
ER	Emergency Room
EU	European Union
GRADE-Methodology	Grading of Recommendations, Assessment, Development and Evaluation Methodology
HRAPIE-Project	Health Risk of Air Pollution in Europe Project
ICD	International Statistical Classification of Diseases and Related Health Problems
OHAT	Office of Health Assessment and Translation
PM	Particulate Matter (Feinstaub)
UBA	German Environment Agency
US EPA	United States Environmental Protection Agency
WHO	World Health Organization
WHO AQG	World Health Organization Air quality guideline

Summary

This documentation contains the technical description of the revised risk-based Air Quality Index (AQI) of the German Environment Agency (Umweltbundesamt, UBA), which is based on the latest World Health Organization (WHO) Air Quality Guidelines published in 2021. The aim of this comprehensive air quality index is to protect from adverse health impacts of air pollution. A risk-based index aims to integrate the risk of health effects from pollutants into its structure and into the evaluation of air quality. This is intended to provide the population with health-relevant information on air quality and recommendations on preventive behavior for the situation at hand.

This technical report comprises several parts describing the concept and the steps involved in creating the index.

The risk-based UBA AQI comprises five assessment categories (from “very good” to “very poor”) for each pollutant, with each assessment category reflecting comparable manifestations of health risks regardless of the pollutant. This means that the recommended health-related behaviour is independent of the pollutant determining the overall index. The assessment categories are therefore risk-equivalent. The risk-based index is built on linear exposure-response relationships for the short-term effect of air pollutants in terms of various health endpoints.

The derivation of the risk-based UBA AQI is based on an adaptation of the methodology developed for the Dutch index (Dusseldorp et al. 2014):

1. Definition of exposure-outcome pairs (proven or probable causality, public health relevance)
2. Literature search of epidemiological reviews on health effects for the specified exposure-outcome pairs
3. Quality assessment of the reviews and extraction or calculation of effect estimates for the specified exposure-outcome pairs
4. Transformation of daily effect estimations to hourly effect estimations
5. Standardization of the pollutant effects to $PM_{2.5}$ as a reference pollutant
6. Definition of assessment categories for $PM_{2.5}$ using the WHO AQG 2021
7. Calculation of risk-equivalent assessment categories for the other pollutants; medical and epidemiological review of the category thresholds

The category thresholds of the risk-based AQI can be found in Table 1.

Table 1: Risk-based UBA AQI, including category thresholds

	Hourly mean values in µg/m³				
Index	**NO_2**	**PM_{10}**	**$PM_{2.5}$**	**O_3**	**SO_2**
Very poor	>100	>90	>50	>240	>100
Poor	61-100	55-90	31-50	145-240	61-100
Moderate	31-60	28-54	16-30	73-144	31-60
Good	11-30	10-27	6-15	25-72	11-30
Very good	0-10	0-9	0-5	0-24	0-10

The reference pollutant used is $PM_{2.5}$, for which the most scientific evidence for exposure-outcome relationships is available. In addition, the alert and information thresholds for the upper class limits were applied for all pollutants. The risk-based UBA LQI is thus risk-based and health-based on the one hand, but on the other hand uses scientifically derived recommendations (WHO AQG 2021 for $PM_{2.5}$) as anchor points in the lower assessment classes and legally defined alert and information thresholds in the highest assessment class.

Based on the updated category thresholds and the resulting assessment categories of the UBA AQI, health-related behavioural recommendations were developed along with corresponding explanations. The behavioural recommendations are differentiated according to sensitivity to the effects of air pollutants (general population and sensitive groups such as individuals with pre-existing conditions, old or very young individuals, pregnant women). Due to the intended use of the index for short-term behavioural adjustment, the recommendations focus on short-term effects, although long-term effects, concentrations and the spatial characteristics of pollution measurements are addressed as well.

The general information contains statements on air quality, risk increases and the population groups affected. The health-related behavioural recommendations were subdivided into recommendations for particularly sensitive groups and for the general population. The other behavioural recommendations provide general advice on how to avoid or reduce emissions, particularly with regard to transport, heating and the use of combustion engines outside the transport sector.

A proposal for behavioural recommendations for the new AQI was given in Table 2.

Table 2: Proposed behavioural recommendations for the new AQI

Index	**Risk**	**Health-related behaviour**		
	General information	**General public**	**Particularly sensitive groups**	**Other behavioural recommendations**[1]
Very poor	The current air quality is very poor. Health issues may arise. Individuals with pre-existing lung and cardiovascular diseases, children and the elderly are most at risk, but even healthy people may experience health effects.	Postpone physically demanding activities or relocate them to places with better air quality. If you experience health effects such as coughing or shortness of breath, you should reduce your physical activity.	Avoid physical exertion outdoors. Postpone physically demanding activities or relocate them to places with better air quality. If you experience any health effects such as coughing or shortness of breath, you should stop your physical activity and review your medication with your doctor.	You can help to ensure that air pollution stops rising and starts falling by leaving your car at home. Use public transport and walk or cycle shorter distances. Form carpool instead of driving alone. Do not burn wood in stoves or fireplaces and refrain from lighting any kind of fire outdoors. Do not use any equipment with combustion engines for hobbies or garden work.
Poor	The current air quality is poor. Health issues may arise. Individuals with pre-existing lung and	If you exercise outdoors, you should choose an area with better air quality	Postpone physically demanding activities or	

Index	**Risk**	**Health-related behaviour**		
	General information	**General public**	**Particularly sensitive groups**	**Other behavioural recommendations[1]**
	cardiovascular diseases, children and the elderly are most at risk.	(e.g. low traffic). If you experience health effects such as coughing or shortness of breath, you should reduce your physical activity.	relocate them to places with better air quality. Alternatively, reduce the level of your physical exertion. If you experience any health effects such as coughing or shortness of breath, you should stop your physical activity and review your medication with your doctor.	
Moderate	The current air quality is moderate. Particularly sensitive people may experience health problems. Individuals with pre-existing lung and cardiovascular diseases are most at risk.	Enjoy your usual outdoor activities.	If you exercise outdoors, you should choose an area with better air quality (e.g. low traffic) and pay attention to possible health effects. If you repeatedly experience health effects such as coughing or shortness of breath, you should reduce your physical activity and review your medication with your doctor.	You can help to ensure that air pollution does not rise or starts falling by leaving your car at home. Use public transport and walk or cycle shorter distances. Form carpool instead of driving alone. If possible, do not use any equipment with combustion engines for hobbies or garden work.
Good	The current level of air pollution is low. Short-term health problems due to air pollution are unlikely. However, effects on chronic diseases cannot be ruled out in the event of long-term exposure at this level.	Enjoy your outdoor activities.	Enjoy your outdoor activities.	You can help keep the air pollution low by leaving your car at home, using public transport and walking or cycling shorter distances. Form carpool instead of driving alone. If possible, do not use any equipment with combustion engines for hobbies or garden work.
Very good	The current level of air pollution is very low. No health problems are	Enjoy your outdoor activities.	Enjoy your outdoor activities.	

Index	Risk	Health-related behaviour		Other behavioural recommendations[1]
	General information	General public	Particularly sensitive groups	
🟦	expected to be caused by air pollutants.			

[1] The advice for “Other behavioural recommendations” was largely adopted from the Swiss air quality index and the WHO recommendations for the design of air quality indices (König Minger et al. 2020; WHO 2023)

With regard to preventive health protection, it was recommended that the risk-based index be used as the future AQI for Germany.

Zusammenfassung

Diese Dokumentation enthält die technische Beschreibung des überarbeiteten risikobasierten Luftqualitätsindex (LQI) vom Umweltbundesamt (UBA), der auf den neuesten Luftqualitätsleitlinien der Weltgesundheitsorganisation (WHO) von 2021 fußt. Dieser umfassende LQI soll zum Schutz vor gesundheitlichen Auswirkungen durch Luftverschmutzung beitragen. Ein risikobasierter Index zielt darauf ab, das Risiko für Gesundheitseffekte von Schadstoffen in die Struktur und die Bewertung der Luftqualität des Index zu integrieren. Hierdurch soll die Bevölkerung für die jeweilig vorliegende Situation mit gesundheitlich relevanten Informationen zur Luftqualität und mit Empfehlungen über präventive Verhaltensweisen versorgt werden.Der hier vorliegende technische Bericht umfasst mehrere Teile, in denen das Konzept und die Schritte zur Erstellung des Index beschrieben werden.

Der risikobasierte UBA LQI umfasst für jeden Schadstoff gestufte Bewertungsklassen (fünf Stufen von „sehr gut“ bis „sehr schlecht“), wobei unabhängig vom Schadstoff die gleiche Bewertungsklasse vergleichbar stark ausgeprägte gesundheitliche Risiken widerspiegelt. Das bedeutet, dass es für die gesundheitlichen Verhaltensempfehlungen nicht von Bedeutung ist, welcher Schadstoff den Gesamtindex bestimmt. Die Bewertungsklassen sind somit risikoäquivalent. Der risikobasierte Index basiert auf linearen Expositions-Wirkungsbeziehungen zur kurzfristigen Wirkung von Luftschadstoffen im Hinblick auf verschiedene Gesundheitsendpunkte.

Die Ableitung des risikobasierten UBA LQI beruht auf einer Adaptation der Methodik, die für den niederländischen Index entwickelt wurde:

1. Festlegung von Expositions-Endpunktpaaren (nachgewiesene oder wahrscheinliche Kausalität, Public Health Relevanz)
2. Literaturrecherche zu epidemiologischen Übersichtsarbeiten zu Gesundheitseffekten für die festgelegten Expositions-Endpunktpaare
3. Qualitätsbeurteilung der Übersichtsarbeiten und Extraktion bzw. Berechnung der Effektschätzer für die festgelegten Expositions-Endpunktpaare
4. Transformation von Effektschätzern für Tagesmittelwerte in Effektschätzer basierend auf Stundenwerten
5. Standardisierung der Schadstoffwirkungen auf Feinstaub ($PM_{2.5}$) als Referenzschadstoff
6. Festlegung von Bewertungsklassen für $PM_{2.5}$ mittels WHO AQG 2021
7. Berechnung von risikoäquivalenten Bewertungsklassen für die anderen Schadstoffe und medizinisch-epidemiologische Überprüfung und Anpassung der Klassengrenzen

Die Klassengrenzen des risikobasierten LQI können Tabelle 1 entnommen werden.

Tabelle 1: Risikobasierter UBA LQI, inklusive der Klassengrenzen

	Stundenmittelwerte in $\mu g/m^3$				
Index	**NO_2**	**PM_{10}**	**$PM_{2.5}$**	**O_3**	**SO_2**
Sehr schlecht	>100	>90	>50	>240	>100
Schlecht	61-100	55-90	31-50	145-240	61-100
Mäßig	31-60	28-54	16-30	73-144	31-60
Gut	11-30	10-27	6-15	25-72	11-30

	Stundenmittelwerte in µg/m³				
Sehr gut	0-10	0-9	0-5	0-24	0-10

Als Referenzschadstoff wird $PM_{2.5}$ genutzt, für den die meiste wissenschaftliche Evidenz für Expositions-Wirkungsbeziehungen vorliegt. Darüber hinaus wurden die Alarm- bzw. Informationsschwellen für die obersten Klassengrenzen für alle Schadstoffe angewendet. Der risikobasierte UBA LQI ist somit einerseits risikobasiert und gesundheitlich begründet, nutzt aber andererseits als Ankerpunkte wissenschaftlich abgeleitete Empfehlungen (WHO AQG 2021 für $PM_{2.5}$) in den unteren Bewertungsklassen und gesetzlich festgelegte Alarm- und Informationsschwellen in der obersten Bewertungsklasse.

Auf Basis der aktualisierten Klassengrenzen und daraus folgenden Bewertungsklassen des UBA LQI wurden für den risikobasierten Index gesundheitsbezogene Verhaltensempfehlungen und Begründungen für diese Verhaltensempfehlungen entwickelt. Die Verhaltensempfehlungen sind differenziert nach Vulnerabilität für die Wirkung von Luftschadstoffen (Allgemeinbevölkerung, vulnerable Gruppen wie Vorerkrankte, alte oder sehr junge Menschen, Schwangere). Aufgrund des vorgesehenen Einsatzes des Index zur kurzfristigen Verhaltensanpassung stehen bei den Verhaltensempfehlungen die kurzfristigen Wirkungen im Vordergrund. Es wurde darüber hinaus der räumliche Bezug der Schadstoffmessungen und Schadstoffkonzentrationen thematisiert.

Für jede Bewertungsklasse werden allgemeine Hinweise zur Risikoerhöhung und zu gesundheitsbezogenem Verhalten gegeben. Darüber hinaus werden Empfehlungen zur Reduktion von Emissionen gegeben. Die allgemeinen Hinweise enthalten Aussagen über die Luftqualität, die Risikoerhöhungen und die betroffenen Bevölkerungsgruppen. Für die gesundheitsbezogenen Verhaltensempfehlungen wird eine Unterteilung der Empfehlungen für besonders empfindliche Gruppen und für die Allgemeinbevölkerung vorgenommen. Die sonstigen Verhaltenshinweise geben allgemeine Ratschläge zur Vermeidung oder Reduktion von Emissionen, die sich vor allem auf den Verkehr, auf das Heizen und auf die Nutzung von Verbrennungsmotoren außerhalb des Verkehrssektors beziehen.

Ein Vorschlag zu Verhaltensempfehlungen für den neuen LQI wurde in Tabelle 2 gegeben.

Tabelle 2: Vorschlag zu Verhaltensempfehlungen für den neuen LQI

Index	Risiko	Gesundheitsverhalten		
	Allgemeine Hinweise	Allgemeinbevölkerung	Besonders empfindliche Gruppen	Sonstige Verhaltenshinweise[1]
Sehr schlecht	Die momentane Luftqualität ist sehr schlecht. Gesundheitliche Beschwerden können auftreten. Betroffen sind am ehesten Personen mit bereits bestehenden Lungen- und Herz-Kreislauferkrankungen, Kinder und ältere Personen, aber auch bei gesunden Menschen	Verlagern Sie körperlich anstrengende Aktivitäten in Zeiten oder an Orte mit besserer Luftqualität. Bei Beschwerden wie z. B. Husten oder Kurzatmigkeit sollten Sie Ihre körperliche Aktivität reduzieren.	Vermeiden Sie körperliche Anstrengung im Freien. Verlagern Sie körperlich anstrengende Tätigkeiten in Zeiten oder an Orte mit besserer Luftqualität. Bei Beschwerden wie z. B. Husten oder Kurzatmigkeit	Damit die Luftbelastung nicht weiter ansteigt und wieder besser wird, können Sie selber dazu beitragen, indem Sie Ihr Auto zu Hause lassen. Benutzen Sie öffentliche Verkehrsmittel und legen Sie kürzere Strecken zu Fuß oder

Index	Risiko	Gesundheitsverhalten		
	Allgemeine Hinweise	**Allgemeinbevölkerung**	**Besonders empfindliche Gruppen**	**Sonstige Verhaltenshinweise[1]**
🟥	können Beschwerden auftreten.		sollten Sie Ihre körperliche Aktivität beenden und mit Ihrer Ärztin/Ihrem Arzt Ihre Medikamente besprechen.	mit dem Fahrrad zurück. Bilden Sie Fahrgemeinschaften, statt alleine in einem Auto zu fahren. Verbrennen Sie kein Holz in Öfen oder Kaminen und verzichten Sie auf jede Art von Feuer im Freien. Verwenden Sie im Hobby- und Gartenbereich keine Geräte mit Verbrennungsmotoren.
Schlecht	Die momentane Luftqualität ist schlecht. Gesundheitliche Beschwerden können auftreten. Betroffen sind am ehesten Personen mit bereits bestehenden Lungen- und Herz-Kreislauferkrankungen, Kinder und ältere Personen.	Wenn Sie draußen Sport treiben, sollten Sie eine Gegend mit besserer Luftqualität (z. B. wenig Verkehr) bevorzugen. Bei Beschwerden wie z. B. Husten oder Kurzatmigkeit sollten Sie Ihre körperliche Aktivität reduzieren.	Verlagern Sie körperlich anstrengende Aktivitäten in Zeiten oder an Orte mit besserer Luftqualität oder reduzieren Sie Ihre körperliche Anstrengung. Bei Beschwerden wie z. B. Husten oder Kurzatmigkeit sollten Sie Ihre körperliche Aktivität beenden und mit Ihrer Ärztin/Ihrem Arzt Ihre Medikamente besprechen.	
Mäßig	Die momentane Luftqualität ist mäßig. Ein Auftreten von gesundheitlichen Beschwerden ist bei besonders empfindlichen Menschen möglich. Betroffen sind am ehesten Personen mit bereits bestehenden Lungen- und Herz-Kreislauferkrankungen.	Genießen Sie Ihre üblichen Aktivitäten im Freien.	Wenn Sie draußen Sport treiben, sollten Sie eine Gegend mit besserer Luftqualität (z. B. wenig Verkehr) bevorzugen und auf mögliche Beschwerden achten. Bei wiederholten Beschwerden wie z. B. Husten oder Kurzatmigkeit sollten Sie Ihre körperliche Anstrengung reduzieren und mit Ihrer Ärztin/Ihrem Arzt	Damit die Luftbelastung weiterhin mäßig bleibt oder wieder besser wird, können Sie selber dazu beitragen, indem Sie Ihr Auto zu Hause lassen. Benutzen Sie öffentliche Verkehrsmittel und legen Sie kürzere Strecken zu Fuß oder mit dem Fahrrad zurück. Bilden Sie Fahrgemeinschaften, statt alleine in einem Auto zu fahren. Verwenden Sie im Hobby- und Gartenbereich möglichst keine Geräte

Index	Risiko	Gesundheitsverhalten		
	Allgemeine Hinweise	Allgemeinbevölkerung	Besonders empfindliche Gruppen	Sonstige Verhaltenshinweise[1]
🟨			Ihre Medikamente besprechen.	mit Verbrennungsmotoren.
Gut	Die momentane Belastung mit Luftschadstoffen ist gering. Es sind kaum kurzfristige gesundheitliche Beschwerden durch Luftschadstoffe zu erwarten. Allerdings sind bei langfristiger Belastung auf diesem Niveau Auswirkungen auf chronische Erkrankungen nicht ausgeschlossen.	Genießen Sie Ihre Aktivitäten im Freien.	Genießen Sie Ihre Aktivitäten im Freien.	Damit die Luftbelastung weiterhin so gut bleibt, können Sie selber dazu beitragen indem Sie Ihr Auto zu Hause lassen, öffentliche Verkehrsmittel benutzen und kürzere Strecken zu Fuß oder mit dem Fahrrad zurücklegen. Bilden Sie Fahrgemeinschaften, statt alleine in einem Auto zu fahren. Verwenden Sie im Hobby- und Gartenbereich möglichst keine Geräte mit Verbrennungsmotoren.
Sehr gut	Die momentane Belastung mit Luftschadstoffen ist sehr gering. Es sind keine gesundheitlichen Beschwerden durch Luftschadstoffe zu erwarten.	Genießen Sie Ihre Aktivitäten im Freien.	Genießen Sie Ihre Aktivitäten im Freien.	

[1] Die Empfehlungen für die „Sonstigen Verhaltensweisen" wurden überwiegend aus dem Schweizer Luftqualitätsindex und den Empfehlungen der WHO zur Gestaltung von Luftqualitätsindizes übernommen.

Im Hinblick auf den präventiven Gesundheitsschutz wurde empfohlen, den risikobasierten Index als künftigen LQI für Deutschland zu verwenden.

1 Introduction

This documentation contains the technical description of the revised air quality index (AQI) of the German Environment Agency (Umweltbundesamt, UBA). The aim of this comprehensive air quality index is to protect from adverse health impacts of air pollution. By providing a clear and comprehensible assessment of air quality, it empowers citizens to protect their health and fosters initiatives to reduce harmful emissions, ultimately improving public health.

The revised AQI was developed as a risk-based approach and is based on the latest World Health Organization (WHO) Air Quality Guidelines published in 2021. A risk-based index aims to integrate the risk of health effects from pollutants into its structure and into the evaluation of air quality.

The present technical report comprises several parts that describe the concept and the steps involved in creating the index. In the following, the WHO Air Quality Guidelines (WHO AQG) of 2021 will be referred to as WHO AQG 2021 to avoid confusion with the European Union (EU) Ambient Air Quality Directive.

1.1 Risk-equivalent assessment categories

The aim of the risk-based AQI developed here is to create a clear link between current air quality and the risk of health consequences. It is intended to provide the public with health-related information on air quality and recommendations on preventive behaviour for the situation at hand. The risk-based UBA AQI comprises five assessment categories (from “very good” to “very poor”) for each pollutant, with each assessment category reflecting comparable manifestations of health risks regardless of the pollutant. In other words, the recommended health-related behaviour is independent of the pollutant determining the overall index. This is referred to as the risk equivalence of the assessment categories.

1.2 Normative documents

1.2.1 EU Ambient Air Quality Directive

The draft of the revised EU Ambient Air Quality Directive is one of the foundations for the risk-based UBA AQI. The EU Ambient Air Quality Directive is the primary regulatory framework for setting air quality standards in the member states of the European Union. At the time of writing, the revised EU Ambient Air Quality Directive had not yet been adopted. The published text of the “Directive of the EU Parliament and of the Council on ambient air quality and cleaner air for Europe” of 26 October 2022 (hereinafter referred to as European Commission (EC) Draft 2022; (Europäische Kommission 2022)) provides the framework for the proposed risk-based UBA AQI. References to more recent versions of the revised directive are marked as such.

The EC Draft 2022 contains the latest version of the European air quality standards in the form of detailed and binding thresholds as well as non-binding target values for air quality. Its main purpose is not to represent the scientific evidence on the link between air quality and health, but rather to take into account regional considerations and the political and economic conditions that are specific to the European context. The proposed standards are therefore not primarily health-based, in contrast to the WHO AQG 2021.

The EC Draft 2022 requires each Member State to provide its population with an assessment of air quality for the pollutants particulate matter 2.5 ($PM_{2.5}$), particulate matter 10 (PM_{10}), nitrogen dioxide (NO_2), ozone (O_3) and sulfur dioxide. (SO_2) on an hourly basis in the form of an index. This index should be based on the WHO AQG 2021.

In April 2024, the EU Ambient Air Quality Directive, which had been revised in trilogue negotiations, was formally adopted by the EU Parliament (EU-Parlament 2024). This adopted version includes updated alert and information thresholds for air pollutants, which serve as triggers for public notifications and measures to mitigate potential health risks associated with elevated pollutant levels. For the first time, it also sets out alert and information thresholds for particulate matter (EU-Parlament 2024). These thresholds have been taken into account in the development of the risk-based UBA AQI. This version also contains some specific provisions for informing the public. It is emphasised that recommendations on behaviour (physical activity outdoors, monitoring of symptoms) should be given for the general population and for sensitive groups (EU-Parlament 2024). This, too, has been considered in the development of the risk-based UBA AQI. Due to the timeline of the present project, the April 2024 document is used in this technical documentation as a reference for the alert and information thresholds and for the notification requirements.

1.2.2 WHO AQG 2021

The main objective of the WHO AQG 2021 is to define globally valid recommendations for maximum concentrations of air pollutants based on their health effects. The WHO air pollutant concentrations for 2021 are not thresholds but recommendations and are therefore referred to below as recommended levels. These levels should not be understood as thresholds below which no health effects occur but rather as values above which there is a high certainty of the risk of serious health effects being increased. This means that health effects can occur even below the respective levels. The WHO AQG 2021 provide a comprehensive framework for assessing air quality and its impact on public health. As such, they serve as an important reference document and contain a comprehensive overview of the relevant literature.

Beyond recommended levels, the WHO AQG 2021 also include so-called interim targets. These are higher than the recommended levels and can be used by authorities in countries with high air pollution to develop step-by-step measures to reduce it. They should be considered as aids and intermediate steps on the way to achieving the recommended levels.

Table 3 contains a detailed breakdown of the guidelines for various air pollutants and averaging times.

Table 3: WHO AQG 2021 levels and interim targets for long-term (annual mean) and short-term (24-hour or 8-hour mean) air pollution (WHO AQG 2021).*

Pollutant	Averaging time	Interim target				WHO AQG recommended level
		1	2	3	4	
$PM_{2.5}$, µg/m^3	1 year	35	25	15	10	5
	24 hours	75	50	37.5	25	15
PM_{10}, µg/m^3	1 year	70	50	30	20	15
	24 hours	150	100	75	50	45
O_3, µg/m^3	Peak season [a]	100	70	-	-	60
	8 hours	160	120	-	-	100
NO_2, µg/m^3	1 year	40	30	20	-	10

Pollutant	Averaging time	Interim target				WHO AQG recommended level
		1	2	3	4	
	24 hours	120	50	-	-	25
SO_2, µg/m^3	24 hours	125	50	-	-	40
CO, mg/m^3	24 hours	7	-	-	-	4

[a] average of daily maximum 8-hour mean O_3 concentration in the six consecutive months with the highest six-month running average O_3 concentration. * The levels from the WHO AQG 2005 for shorter averaging times have not been revised and remain valid (WHO AQG 2006).

1.3 Relevance of the WHO AQG levels and interim targets in defining the assessment categories

Since the WHO AQG 2021 levels are used for the AQI, this section explains what these levels represent and what consequences arise from the methodology used to derive these levels for use in an AQI. The WHO AQG 2021 do not represent thresholds at which effects occur but rather levels above which the risk of serious health effects (e.g. mortality) is extremely likely to increase. Health effects also occur below the WHO AQG 2021 levels; however, they cannot be demonstrated with the same certainty as established in the WHO AQG 2021 methodology. Furthermore, it is important to know that the levels for short-term exposure are derived from the levels for long-term exposure. The WHO AQG 2021 are therefore by virtue of their definition dependent on the quality and quantity of scientific studies for long-term health effects. The more high-quality studies for low concentrations exist, the more probable it is that the required level of certainty has been achieved, and the lower the corresponding AQG levels for long-term and short-term concentrations. The WHO AQG levels, therefore, do not represent risk-equivalent concentrations.

Using the WHO AQG 2021 in the specifications of the EU Ambient Air Quality Directive for the European indices represents a commitment to the latest scientific advances and international standards in the field of air quality assessment and is aimed at ensuring a comprehensive and evidence-based approach to dealing with health effects related to air quality.

2 Derivation of the risk-based UBA AQI

2.1 Rationale

The fundamental idea of a risk-based AQI is that the risk for the assessed health effects is the same for each assessment category, regardless of the specific pollutant. Thus, the assessment categories are risk equivalent. This means, for example, that the risk of hospital admissions for respiratory diseases in the "moderate" assessment category is increased by the same percentage compared to zero exposure to pollutants, regardless of which pollutant is responsible for the classification in this assessment category. A similar approach was used to create the air quality index in the Netherlands (Dusseldorp et al. 2014).

The risk-based index is built on linear exposure-response relationships for the short-term effect of air pollutants in terms of various health endpoints. To achieve the desired risk equivalence between the different pollutants, the health effects of the pollutants included in the index were standardised to the effects of $PM_{2.5}$.

A risk-based AQI consisting of different assessment categories requires a definition of the risk increases on which the classification is based. However, in the case of the linear exposure-response relationships available for air pollutants, there are no biological effect thresholds that can be defined as index thresholds. Ultimately, this problem can only be solved with a normative definition of index thresholds, which is carried out in the risk-based UBA AQI using the WHO AQG 2021.

2.2 Input data

The index is based on hourly measurements of air pollutant concentrations in order to take into account short-term changes and peak levels, and to assess current air quality with the least possible delay. This allows for timely communication of increased health risks to the population, in particular, to sensitive groups, enabling people to change their behaviour immediately, which can reduce the incidence of symptoms of existing conditions and have a preventive effect on general health outcomes.

Since there are no epidemiological studies on the health effects of very short-term (hourly) exposures, but the index is to be based on hourly measurements, the risk-based UBA AQI includes a procedure for transforming effect estimates from 24-hour averaging times for the respective pollutants into effects for hourly exposure.

The switch to hourly values for particulate matter ($PM_{2.5}$, PM_{10}) is one of the major changes compared to the previous method of deriving the UBA AQI used since the introduction of an air quality app for smartphones in 2019 (Tobollik et al. 2021).

2.3 Index formation

The risk-based UBA AQI covers the five individual pollutants specified by law: $PM_{2.5}$, PM_{10}, NO_2, O_3 and SO_2 (Europäische Kommission 2022). Each pollutant is first assessed individually on a five-point scale, using the categories "very good", "good", "moderate", "poor" and "very poor". The individual pollutant assessments are then summarised in an overall index, which is based on the worst individual pollutant category and thus carries the same qualitative designations. The presence of at least one pollutant is sufficient to derive an overall index. If a measuring station does not measure all pollutants, the overall index is displayed in the UBA's air quality app as an incomplete circle (e.g. a 2/3 filled pie chart when a pollutant is not measured, known as a "Pac-Man"), to make it clear that no information is available for some pollutants and that the overall assessment may underestimate the actual pollution. This type of index formation is identical to the currently used UBA AQI described in 2021 (Tobollik et al. 2021).

2.4 Derivation methodology

The derivation of the risk-based UBA AQI is based on an adaptation of the methodology developed for the Dutch index (Dusseldorp et al. 2014).

2.5 Overview

1. Definition of exposure-outcome pairs (causality, public health relevance)
2. Literature search of epidemiological reviews on health effects for the specified exposure-outcome pairs and data extraction
3. Quality assessment of the reviews and extraction or calculation of effect estimates for the specified exposure-outcome pairs
4. Transformation of daily to hourly values
5. Standardization of the pollutant effects to $PM_{2.5}$ as a reference pollutant
6. Definition of assessment categories for $PM_{2.5}$ using the WHO AQG 2021
7. Calculation of risk-equivalent assessment categories for the other pollutants; medical and epidemiological review of the category thresholds

These steps are described in detail below.

3 Step 1: Definition of exposure-outcome pairs

Ideally, an air quality index should warn of all types of adverse health effects. The short-term effects that are the focus of attention here include, in descending order of frequency, physiological changes (biomarkers of inflammation, oxidative stress, coagulation, etc.), symptoms (including coughing, wheezing, shortness of breath, tightness in the chest, cardiac irregularities, tachycardia, dizziness, headaches, etc.), impaired organ function, increased medication use, emergencies and hospital admissions, as well as deaths. Deaths are obviously the worst possible endpoint of increased exposure, but at the same time also the rarest. The population should also be protected from the significantly more frequent and, at lower levels, more pronounced manifestations of disease, which means preventing increased medication intake, emergencies and hospital admissions.

With this aim in mind, the development of the risk-based UBA AQI was primarily based on studies analysing the short-term effects of air pollutants on emergencies and hospital admissions. In addition, mortality was also included in order to expand the evidence base. The risk-based UBA AQI therefore mainly focuses on outcomes that play a major role for public health both due to their frequency and their medical impact. Markers for physiological changes were not included as outcomes because the underlying studies were often conducted in smaller and highly selected populations, and the actual health significance of these biomarker changes cannot be established.

3.1 Selected exposure-outcome pairs

Outcomes with a causal or likely causal relationship with several air pollutants in the index were selected. The evidence for these relationships with the selected endpoints is based on numerous primary studies. The following outcomes were taken into account for the calculation of the index:

- Hospital admissions for cardiovascular diseases
- Hospital admissions for respiratory diseases
- Emergency room (ER) visits or hospital admissions for asthma
- All-cause mortality (natural mortality, classified according to the International Statistical Classification of Diseases and Related Health Problems (ICD) ICD-10: A00 to R99)

The assessments of the United States Environmental Protection Agency (US EPA), taken from the regularly revised interactive graphic of the Swiss Tropical and Public Health Institute (Schweizerisches Tropen- und Public-Health-Institut 2024), were used to determine the causality of the relationships with the pollutants included in the index. A causal effect is assumed when it has been demonstrated that a pollutant has a health impact in case of population-based exposures, based on studies covering multiple lines of evidence (cellular, experimental animal, experimental human and epidemiological studies). Random results, confounding factors and other distortions must be ruled out with sufficient probability (US EPA 2015, 2024a, 2024b, 2024c). In addition, the assessments of the level of certainty of the evidence contained in the reviews on which the WHO AQG 2021 is based were used. Some of these reviews are more up to date than the US EPA documents and contain a standardised evaluation of the evidence.

3.1.1 Particulate matter

Short-term increases in the concentration of particulate matter ($PM_{2.5}$ and PM_{10}) are causally linked to a number of outcomes including non-accident mortality and mortality due to cardiovascular disease (CVD), to effects on the cardiovascular system such as high blood pressure and cardiac arrhythmia, and to emergencies due to cardiovascular disease. In addition, short-term effects on the respiratory tract are assumed to be likely causal for an exacerbation of existing diseases, an increase in symptoms or medication use in patients with asthma and chronic obstructive pulmonary disease (COPD), emergencies due to respiratory diseases or COPD, and mortality due to respiratory diseases.

3.1.2 Gases

Short-term increases in the concentration of NO_2 and SO_2 have a causal effect on mortality from respiratory diseases. The effects of a short-term increase in the concentrations of O_3, SO_2 and NO_2 on respiratory diseases and emergencies due to asthma, respiratory diseases (O_3 only) and COPD (O_3 only) are also classified as causal. The US EPA has not yet classified the relationship between O_3, SO_2 and NO_2 and all-cause mortality as causal or likely causal. However, the level of evidence for the relationships was assessed as “high certainty” in the more recent reviews for the WHO AQG 2021 (Orellano et al. 2020; Orellano et al. 2021). So far, there are no assessments of causal or likely causal effects of short-term increases in concentrations of O_3, SO_2 or NO_2 on CVD or emergencies due to CVD.

4 Step 2: Literature search

4.1 Search strategy

To identify relevant reviews, we used the PubMed search engine to search MEDLINE for epidemiological reviews and meta-analyses on short-term effects (24-hour or 8-hour exposure) for the above-mentioned exposure-response relationships. There were no temporal or geographical restrictions on the search; the languages were limited to English and German. For the risk-based UBA AQI, the estimates for health effects were extracted from the identified reviews and meta-analyses on the short-term effects of air pollutants (NO_2, $PM_{2.5}$, PM_{10}, O_3 and SO_2) on ER visits, hospital admissions and mortality. Daily averages (24 hours) were extracted for PM_{10}, $PM_{2.5}$, NO_2 and SO_2, while 8-hour maximum values were taken for O_3.

Compared to many other regions of the world, Germany has relatively low O_3 concentrations due to its geographical location and temperate climate. For this reason, the search of short-term effects of O_3 on hospital admissions and ER visits was limited to regions that have similar O_3 concentrations. Therefore, estimates from reviews of comparable regions were used as far as the data permitted, or, if possible, new meta-analyses were carried out specifically on the basis of data from comparable climatic regions.

4.2 Selected relative risks

The data sources from which the effect estimates for the defined exposure-outcome pairs were derived are listed below. All effect estimates used are summarised in Table 4 as a percentage increase in cases per 10 µg/m^3 increase in pollutant concentration. As the effect estimates were reported in the results of the relevant studies using varying degrees of precision, the precision was standardized by rounding all estimates to the first decimal place. In cases where the second decimal place contained a five, the number was rounded up.

4.2.1 All-cause mortality

Reviews on the analysis of short-term pollutant levels and mortality (Orellano et al. 2020; Orellano et al. 2021) were included in the present work. These publications are the basis for the WHO AQG 2021. The causes of death considered in this review include mortality from natural causes (ICD-10: A00 to R99) for all pollutants in the index, mortality from respiratory diseases (ICD-10: J00 to J99) for PM_{10}, $PM_{2.5}$ and SO_2, and cardiovascular (ICD-10: I01 to I59) and cerebrovascular mortality (ICD-10: I60 to I69) for PM_{10} and $PM_{2.5}$. The respective effect estimates per 10 µg/m^3 were taken from Orellano et al. (2020) and Orellano et al. (2021). For total mortality, they are 0.4% (95% CI: 0.3; 0.5) for PM_{10}, 0.7% (95% CI: 0.4; 0.9) for $PM_{2.5}$, 0.4% (95% CI: 0.3; 0.5) for O_3, 0.7% (95% CI: 0.6; 0.9) for NO_2, and 0.6% (95% CI: 0.5; 0.7) for SO_2 per 10 µg/m^3.

4.2.2 O_3 and hospital admissions for asthma

The effect estimate for the association between O_3 and ER visits or hospital admissions for asthma was derived by Zheng et al. (2021). The original effect estimate for O_3, based on 27 studies from different world regions, was 0.8% (95% CI: 0.5; 1.1) per 10 µg/m^3 increase for hospital admissions and ER visits. In agreement with the UBA, it was decided that studies from regions with comparable meteorological conditions should preferably be used to derive the risk in Germany. Hence, a meta-estimate of 0.3% (95% CI: -0.7; 1.5) was identified for the increase in hospital admissions and ER visits per 10 µg/m^3 of O_3, which is based only on four studies from Central and Northern Europe (Greater Paris, Amsterdam, Manchester, London: Medina et al.

1997; Schouten et al. 1996; Wilson et al. 2005; Atkinson et al. 1999). Studies from the Mediterranean region were not used because of the significantly higher O_3 levels there.

4.2.3 O_3 and hospital admissions for respiratory diseases

There is limited evidence for short-term effects of O_3 on hospital admissions for individuals with respiratory diseases. No recent systematic review of the literature on the association between O_3 pollution and hospital admissions for respiratory diseases was identified. The older comprehensive WHO review – the Health Risk of Air Pollution in Europe Project (HRAPIE) (WHO Regional Office for Europe 2013) – was not used for the extraction of relative risks since it adopted the association between O_3 and hospital admissions for respiratory diseases from the "Air Pollution and Health: A Combined European and North American Approach" (APHENA) study (WHO Regional Office for Europe 2013). For Europe, data was available from only eight cities, stratified by respiratory and cardiovascular diseases but only for people aged 65 years and older, and adjusted for PM_{10}. Due to the geographical location of the original studies and the age restriction of the European studies, the data from the HRAPIE project was not used.

In the latest scoping review by Abed Al Ahad et al. (2020), only one study on hospital admissions for respiratory diseases was suitable for deriving short-term effects of O_3 in a temperate climate (Hůnová et al. 2013). This study was conducted in Prague using data from government records and covered a population of approximately 1,200,000. The effect estimate for hospital admissions for respiratory diseases was calculated to be 0.2% (95% CI: -1.1; 1.5) for an increment of 10 $\mu g/m^3$ in the maximum 8-hour concentration of O_3 with a lag of one day (lag1).

A quantitative systematic review of the associations between short-term exposure to O_3 and mortality and hospital admissions for respiratory diseases was published by (Atkinson et al. 2014). The review found a positive association between the eight-hour O_3 concentration (mean) and the increase in hospital admissions for respiratory diseases (0.75% (95% CI: 0.30; 1.19) per 10 $\mu g/m^3$). In the analysis by region, the association between O_3 and all respiratory diseases in Europe was estimated to be 0.14% (95% CI: -0.22; 0.51) per 10 $\mu g/m^3$ and was based on the studies conducted in Nicosia, Paris, Rome, London and the West Midlands. The Prague study (Hůnová et al. 2013) was not included in this systematic review by Atkinson because it was published after the review period (ending May 2011).

On the basis of the above-mentioned studies, the decision was taken to use two sources to estimate the effect of O_3 on hospital admissions for respiratory diseases: the study from the Czech Republic by Hůnová et al. (2013) and the systematic review by Atkinson et al. (2014) for the European region. A weighted average of the two available estimates (0.20% (95% CI: -1.1; 1.5) and 0.14% (95% CI: -0.22; 0.51)) could not be calculated due to the sparse data. Therefore, the effect estimate for hospital admissions for respiratory diseases due to short-term O_3 exposure was set as the unweighted mean of the estimates from the two studies and rounded to 0.2% (95% CI: -0.2; 0.5).

4.2.4 $PM_{2.5}$ and asthma

The effect estimates for $PM_{2.5}$ and ER visits or hospital admissions for asthma due to $PM_{2.5}$ exposures were taken from the systematic literature review on non-fatal effects of $PM_{2.5}$ (Ru et al. 2023). The study provides two separate effect estimates for hospital admissions and ER visits: 1.4% (95% CI: 0.8; 2.0) and 4.3% (95% CI: 2.6; 6.2) per 10 $\mu g/m^3$, respectively. However, to be formally consistent with other sources, the effect estimate for asthma-related outcomes should include both ER visits and hospital admissions. Therefore, the mean of these values was used, resulting in a $PM_{2.5}$ effect estimate for ER visits or hospital admissions for asthma of 2.9% (95% CI: 1.7; 4.1) per 10 $\mu g/m^3$.

4.2.5 PM_{10} and asthma

A slightly older systematic review of the literature on asthma-related endpoints (Zheng et al. 2015), conducted by the same group of authors as Zheng et al. (2021) with similar inclusion and exclusion criteria, provided the relative risks for PM_{10} which were included in the calculations. The effect estimate for the increase in ER visits or hospital admissions for asthma per 10 $\mu g/m^3$ of PM_{10} is 1.0% (95% CI: 0.8; 1.3).

4.2.6 $PM_{2.5}$ and respiratory diseases

The effect estimate for respiratory diseases in case of $PM_{2.5}$ exposures was taken from the systematic literature review on non-fatal effects of $PM_{2.5}$ (Ru et al. 2023). For a 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration, the effect estimate for hospital admissions for respiratory diseases is 1.4% (95% CI: 1.0; 1.7).

4.2.7 PM_{10} and respiratory diseases

The effect estimate for PM_{10} and respiratory diseases was taken from the latest scoping literature review (Abed Al Ahad et al. 2020). This review was conducted as a narrative summary of the literature on the association of air pollution and weather with mortality and hospital admissions without a meta-analysis. For the present project, the detailed description of the studies and the individual effect estimates were used to calculate a weighted meta-estimate for a 10 $\mu g/m^3$ increase in pollutant concentration. Only studies with a delayed effect assessment (lag) of ≤2 days were used (Basagaña et al. 2015; Tomášková et al. 2016). Based on these sources, the effect estimate for hospital admissions for respiratory diseases due to PM_{10} is 1.6% (95% CI: 0.04; 3.14) (authors' calculation as a weighted average from the two studies cited above).

4.2.8 $PM_{2.5}$ and cardiovascular diseases

The effect estimate for cardiovascular diseases with a 10 $\mu g/m^3$ increase in $PM_{2.5}$ pollution was taken from the systematic literature review on the non-fatal effects of $PM_{2.5}$ (Ru et al. 2023), which reports an effect estimate for hospital admissions for cardiovascular diseases of 1.0% (95% CI: 0.6; 1.4) for a 10 $\mu g/m^3$ increase in $PM_{2.5}$ pollution.

4.2.9 PM_{10} and cardiovascular diseases

The effects of PM_{10} on cardiovascular diseases were taken from the scoping literature review (Abed Al Ahad et al. 2020). For the present project, the detailed description of the studies and the individual effect estimates were used to calculate the weighted average of the percentage increase in hospital admissions for cardiovascular diseases for a 10 $\mu g/m^3$ increase in pollutant concentration. Only studies with a lag of ≤2 days were selected for the effect estimate for PM_{10} and cardiovascular disease (Colais et al. 2012; Stafoggia et al. 2017; Basagaña et al. 2015; Tomášková et al. 2016). The effect estimate for the increase in hospital admissions for cardiovascular diseases is 0.7% per 10 $\mu g/m^3$ of PM_{10} (95% CI: 0.2; 1.1) (authors' calculation).

4.2.10 NO_2 and asthma

The effect estimate for ER visits or hospital admissions for asthma due to NO_2 was derived by Zheng et al. (2021) in the systematic literature review prepared specifically for the publication of the WHO AQG 2021. The effect estimate for the increase in ER visits or hospital admissions for asthma is 1.4% (95% CI: 0.8; 2) per 10 $\mu g/m^3$ pollutant concentration increase.

4.2.11 NO_2 and respiratory diseases

The effect estimate for respiratory diseases at NO_2 levels was taken from the HRAPIE project (WHO Regional Office for Europe 2013). The effect estimate for hospital admissions for respiratory diseases is 1.8% (95% CI: 1.1; 2.5) for NO_2 per 10 µg/m³ increase in pollutant concentration (Anderson et al. 2007, cited in the HRAPIE project).

4.2.12 SO_2 and asthma

The effect estimate for ER visits or hospital admissions for asthma due to SO_2 was derived by Zheng et al. (2021) in a systematic literature review prepared specifically for the publication of the WHO AQG 2021. The effect estimate for hospital admissions for asthma is 1.0% (95% CI: 0.1; 2) for NO_2 per 10 µg/m³ increase in pollutant concentration.

Table 4: Relative risks as excess cases in percent with short-term pollutant exposure (24-hour or 8-hour mean values) per 10 µg/m³ concentration increase

Pollutant	Hospital admissions for cardiovascular diseases in %	Hospital admissions for respiratory diseases in %	ER visits or hospital admissions for asthma in %	Excess mortality in %
$PM_{2.5}$ (24h)	1.0 (0.6; 1.4) [1] a	1.4 (1.0; 1.7) [1] a	2.9 (1.7; 4.1) [1] ***	0.7 (0.4; 0.9) [8]
PM_{10} (24h)	0.7 (0.2; 1.1) [3]	1.6 (0.0; 3.1) [3]	1.0 (0.8; 1.3) [5]	0.4 (0.3; 0.5) [8]
O_3 (8h)	N/A	0.2 (-0.2; 0.5) [6,7] *	0.3 (-0.7; 1.5) [4] **	0.4 (0.3; 0.5) [8]
NO_2 (24h)	N/A	1.8 (1.1; 2.5) [2]	1.4 (0.8; 2) [4]	0.7 (0.6; 0.9) [8]
SO_2 (24h)	N/A	No data	1.0 (0.1; 2) [4]	0.6 (0.5; 0.7) [9]

[1] Ru et al. (2023), [2] WHO Regional Office for Europe (2013); [3] Abed Al Ahad et al. (2020); [4] Zheng et al. (2021); [5] Zheng et al. (2015); [6] Hůnová et al. (2013); [7] Atkinson et al. (2014); [8] Orellano et al. (2020); [9] Orellano et al. (2021); * Mean of estimates in Hůnová et al. (2013) and Atkinson et al. (2014) for the European region only; ** Northern Europe only, comprising the Greater Paris area, Amsterdam, Manchester and London; *** Mean of two linear relative risks of ER visits and hospital admissions for asthma; a Using the linear exposure-response relationship. N/A – not applicable because the evidence for an association is not considered at least likely causal.

If several time-delayed exposure periods (so-called lag periods) were specified in the studies, short lag and averaging times (8-hour or 24-hour) were primarily selected, rather than cumulative lag periods (e.g. the average of the last 48 hours or 72 hours). The details can be found in the cited original publications.

Table 5 shows the time intervals that represent the short-term exposure periods in the selected studies.

Table 5: Covered lag periods in selected studies

Studies	Endpoint	Pollutants	Lag periods of original studies used in the meta-analysis; covered lags (in days)
Ru et al. (2023)	ER visits or hospital admissions for asthma	$PM_{2.5}$	Lag periods and cumulative lag periods in most studies between lag 0 and lag 5, three studies with cumulative lag periods of 0-6, 0-7 and 0-11 days.

Studies	Endpoint	Pollutants	Lag periods of original studies used in the meta-analysis; covered lags (in days)
	Hospital admissions for cardiovascular diseases	$PM_{2.5}$	Lag periods and cumulative lag periods between lag 0 and lag 6
	Hospital admissions for respiratory diseases	$PM_{2.5}$	Lag periods and cumulative lag periods in most studies between lag 0 and lag 3, three studies with lag and cumulative lag periods of 0-6, 14 and 0-14 days.
Abed Al Ahad et al. (2020)	Hospital admissions for cardiovascular diseases	PM_{10}	Lag 0 and cumulative lag period of 0-1
	Hospital admissions for respiratory diseases	PM_{10}	Lag 0
Zheng et al. (2021)	Notfallaufnahmen oder Krankenhauseinweisungen wegen Asthma	O_3	Lag 0 und lag 1
	Notfallaufnahmen oder Krankenhauseinweisungen wegen Asthma	NO_2, SO_2	Lag-Perioden zwischen lag 0 und lag 4
Zheng et al. (2015)	ER visits or hospital admissions for asthma	PM_{10}	Lag periods between lag 0 and lag 7
WHO Regional Office for Europe (2013)	Hospital admissions for respiratory diseases	NO_2	Lag periods between lag 0 and lag 3
Hůnová et al. (2013)	Hospital admissions for respiratory diseases	O_3	Lag 1
Atkinson et al. (2014)	Hospital admissions for respiratory diseases	O_3	Lags 0, 1, 2 and cumulative lag period of 0-1
Orellano et al. (2020)	Excess mortality	$PM_{2.5}$, PM_{10}, NO_2, O_3	Lag periods between lag 0 and lag 7
Orellano et al. (2021)	Excess mortality	SO_2	Lag periods between lag 0 and lag 7

5 Step 3: Quality assessment of the systematic reviews and meta-analyses

We evaluated whether the reviews and meta-analyses included a formal quality assessment of the evidence considered. The systematic quality assessment of individual studies and of the overall evidence contained in a systematic review is a relatively new development. Several tools for analysing the potential risk of bias have been developed in recent years. Therefore, formal and criteria-based quality assessments are often found in current reviews, while older reviews tend to use narrative and thus less standardised methods to assess the quality of the individual studies. A systematic evaluation of the overall evidence, as carried out in tools such as the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) methodology (GRADE | Cochrane Deutschland 2024) or in the tool of the Office of Health Assessment and Translation (OHAT, National Institute of Environmental Health Sciences 2024), is also a rather recent development. The formal quality assessment and the methods applied in the included reviews thus differ considerably in scope and quality, and some of the reviews do not contain any formal quality assessments.

Three articles, Zheng et al. (2021), Orellano et al. (2021) and Orellano et al. (2020), use a modular risk of bias assessment tool developed during the preparation of the WHO AQG 2021 (WHO Global Air Quality Guidelines Working Group on Certainty of Evidence Assessment 2020; WHO Global Air Quality Guidelines Working Group on Risk of Bias Assessment 2021). The assessment of the risk of bias for each study was based on the areas of confounding, sampling error, determination of exposure, measurement of outcomes, missing data and selective reporting. The results for each area were analysed separately. In the studies that analysed the association between air pollutants (NO_2 (24h), SO_2 (24h), O_3 (8h), PM_{10} (24h), $PM_{2.5}$ (24h)) and all-cause mortality for all five pollutants (Orellano et al. 2020; Orellano et al. 2021), it was found that in three out of six areas – namely, sampling errors, determination of exposure and selective reporting – the risk of bias was mostly low or moderate. In contrast, the highest risk of bias was observed for missing data, involving 59% of the exposure-outcome combinations, mainly due to insufficient information on missing values or the application of imputation methods. Using the GRADE approach, the risk of bias in the assessment of O_3 (8h), SO_2 (24h) and NO_2 (24h) and ER visits or hospital admissions for asthma (Zheng et al. 2021) is as follows: in the studies, the risk of bias was particularly high in the area of missing data, as no information was provided on the imputation methods or the extent of the missing data. Furthermore, a bias was observed regarding outcomes, mainly because asthma exacerbations were self-reported and not medically diagnosed, and ICD instruments were not used for classification. Problems regarding confounding were minimal; other areas were not significant in the analysis.

In the publication of a new concentration-response relationship for seven morbidity outcomes associated with short-term $PM_{2.5}$ exposure (Ru et al. 2023), which was used to extract changes in the percentage of hospital admissions for respiratory and cardiovascular diseases and asthma, the possible presence of publication bias in the review was assessed using funnel plots. The potential for publication bias in the meta-analysis was confirmed by the funnel plots for each morbidity outcome in Ru et al. (2023), particularly with regard to asthma-related ER visits for the population as a whole.

In Zheng et al. (2015), the validity of the studies was evaluated based on the methods proposed in the previous systematic reviews by Mustafic et al. (2012). Three components were evaluated to determine quality: the validity of the asthma diagnosis (0 to 1 point), the measurement of air pollutants (0 to 1) and the adjustment for confounding factors (0 to 3). Studies that received five points underwent sensitivity analyses. Potential publication bias was examined and confirmed using Egger’s test.

In the HRAPIE project (WHO Regional Office for Europe 2013), the quality of the studies was assessed by a group of experts, and the degree of certainty for the correct risk estimate for the respective exposure-outcome pairs was categorised in two levels (group A: reliable quantification of the effect size possible; group B: uncertainty regarding the exact quantification of the effect size). For the exposure-outcome pair of NO_2 and respiratory diseases used in this work, the confidence in a correct risk estimate was classified as high (group A).

The systematic review by Atkinson et al. (2014) used various methods to identify indications of bias coming from small studies (Begg und Berlin 1989; Egger et al. 1997; Duval und Tweedie 2000). The effect estimates were corrected for indications of bias from small studies if detected. No evidence of such bias was found for the association between O_3 and hospital admissions for respiratory diseases.

In the scoping literature review by Abed Al Ahad et al. (2020), which was used to extract the effects of PM_{10}, the risk of bias was not assessed. The study by Hůnová et al. (2013) did not describe an assessment of the risk of bias, either.

In summary, an examination of the identified reviews and meta-analyses shows that formal quality assessments of the considered evidence are a relatively new development, with modern tools such as GRADE or OHAT being used to systematically evaluate the evidence base. More recent papers, such as those by Zheng et al. (2021), Orellano et al. (2020) and Orellano et al. (2021), use specific risk-of-bias tools to assess various areas. These tools help to analyse potential risks of bias. Older studies often use less formalised, narrative approaches. The application of the newer methods rarely identifies serious quality issues; in most cases, the quality of the evidence was high. In contrast, other studies, such as those by Abed Al Ahad et al. and Hůnová et al., performed no systematic assessment of the risk of bias. A high risk of bias cannot be ruled out here; however, based on the above-mentioned results, it appears unlikely.

6 Step 4: Transformation of the effect estimates from daily to hourly values

6.1 Definition of the transformation factor

Almost all health outcomes in the studies have a maximum temporal resolution of one day. Only a few studies and study designs provide a higher temporal resolution on these endpoints (e.g. hourly data; for example, in case-crossover studies on heart attacks using exact time data on the onset of the attack). The study base considered here therefore consists primarily of effect estimates related to the 24-hour or 8-hour mean values of air pollutant concentrations. This does not align with the goal of basing the new index on hourly pollutant concentrations and thus rendering it an up-to-date indicator of health concerns.

Since the revised AQI is to be based on measured hourly mean values, a procedure was applied to transform the relative risks based on daily mean values or rolling 24-hour mean values of air pollutant concentrations into relative risks based on 1-hour mean values (see Table 4 for the short-term studies used for this purpose).

This transformation is based on several assumptions, the fundamental one being that the increase in risk for the daily mean or the rolling 24-hour mean is highly correlated with the increase in risk given by the 1-hour daily maximum within this time period. The 1-hour daily maximum is the 1-hour mean value of the hourly interval with the highest pollution during the day. This means that if two time series studies are conducted, one on the association of 24-hour mean values with daily mortality and the other on the association of the 1-hour daily maximum with daily mortality, then the effect estimates resulting from these two studies are highly correlated. Empirical evidence for this assumption can be found among other sources in the literature on the Canadian AQI (Stieb et al. 2008), which showed empirically that the 3-hour or 1-hour daily maximum effects of CO, NO_2, O_3, PM_{10}, $PM_{2.5}$ and SO_2 on all-cause mortality correspond to the effects of the respective 24-hour mean value.

Furthermore, the 1-hour daily maximums of air pollutant concentrations are highly correlated with the 24-hour mean values (Stieb et al. 2008). This means that conclusions may be drawn from the latter regarding the former.

Therefore, a transformation factor, defined as the ratio of the 1-hour daily maximum to the 24-hour mean value of the air pollutant concentrations, was calculated in a first step (Figure 1). The procedure was applied analogously to the O_3 concentration, for which the effect estimator in most studies is based on the maximum 8-hour rolling daily mean (Figure 2).

Figure 1: Equation transformation factor

$$\text{Transformation factor} = \frac{\text{1-hour daily maximum for air pollutant X}}{\text{24-hour mean for air pollutant X}}$$

Source: Own representation, Institute for Occupational, Social and Environmental Medicine, Environmental Epidemiology Working Group, University Hospital Düsseldorf, Heinrich Heine University Düsseldorf.

Figure 2: Equation transformation factor for O_3

$$\text{Transformation factor } O_3 = \frac{\text{1-hour daily maximum for } O_3}{\text{8-hour mean for } O_3}$$

Source: Own representation, Institute for Occupational, Social and Environmental Medicine, Environmental Epidemiology Working Group, University Hospital Düsseldorf, Heinrich Heine University Düsseldorf.

In a second step (transformation of the effect estimates), this transformation factor was applied to the 24-hour effect estimates for the exposure-outcome pairs. For this purpose, these 24-hour effect estimates were divided by the pollutant-specific transformation factor for each pollutant to obtain the hourly risk estimates (Figure 3). For O_3, the respective transformation factor was applied to the 8-hour effect estimates in the same way (Figure 4).

Figure 3: Equation computation of the 1-hour effect estimate

$$\text{1-hour effect estimate air pollutant X} = \frac{\text{24-hour effect estimate}}{\text{transformation factor}}$$

Source: Own representation, Institute for Occupational, Social and Environmental Medicine, Environmental Epidemiology Working Group, University Hospital Düsseldorf, Heinrich Heine University Düsseldorf.

Figure 4: Equation computation of the 1-hour effect estimate for O_3

$$\text{1-hour effect estimate } O_3 = \frac{\text{8-hour effect estimate } O_3}{\text{transformation factor}}$$

Source: Own representation, Institute for Occupational, Social and Environmental Medicine, Environmental Epidemiology Working Group, University Hospital Düsseldorf, Heinrich Heine University Düsseldorf.

This procedure allows the exposure-outcome pairs considered relevant to be used comparatively for the index development despite the insufficient temporal resolution in the primary studies. This approach was also used for the Belgian and Dutch AQIs (irCELine 2022; Dusseldorp et al. 2014). Further transformation factors were examined in sensitivity analyses (99th percentile/24-hour mean and other percentiles), but these had little influence on the final classifications of the UBA AQI.

6.1.1 Empirical measurement data

The calculation of the transformation factors was carried out for all pollutants based on the hourly measurement data from 2019 and 2022. Data from a total of 439 measuring stations was available for 2019, and from 433 measuring stations for 2022. Since only a few of these stations measure all five substances, the number of time series available varied for each pollutant (Table 6).

Table 6: Number of measuring stations per substance and year

Pollutant	Number of measuring stations in 2019	Number of measuring stations in 2022
NO_2	411	409
O_3	272	277
SO_2	115	108
$PM_{2.5}$	218	286
PM_{10}	361	361

6.1.2 Calculation of the transformation factor

For NO_2, SO_2, PM_{10} and $PM_{2.5}$, the calculation of the transformation factor is based on daily mean values calculated according to the 39th Ordinance on the Implementation of the Federal Immission Control Act (BImSchV, 2020) if at least 18 of the 24 hourly measurements were available at a station on a given day. The quotient of the 1-hour daily maximum and the 24-hour daily mean was then calculated for each day and averaged over the respective year to obtain the transformation factor for the above-mentioned pollutants (1-hour maximum/24-hour mean).

For O_3, the calculation of the transformation factor is based on the maximum 8-hour rolling average of a day. 8-hour rolling averages were then formed from the hourly measurement data, where at least six of the eight hours had to be available in accordance with the 39th BImSchV (2020). The calculated 8-hour average was mapped to the end of the averaging period (i.e. the average at 10 a.m. refers to the period between 2 a.m. and 10 a.m.) If at least 18 of the 24 8-hour rolling means were available, the maximum 8-hour rolling mean for that day was determined. The quotient of the 1-hour daily maximum and the maximum 8-hour mean was then calculated for each day and subsequently averaged over the respective year to obtain the transformation factor for O_3 (1-hour maximum/8-hour maximum).

In addition, transformation factors were calculated for a sensitivity analysis based on the 95th percentile (1h P95/24h), the 90th percentile (1h P90/24h) and the 70th percentile (1h P70/24h) of the hours of a day instead of the daily maximum. The transformation factors averaged over the respective year are shown in Table 7.

Table 7: Transformation factors for measurements in Germany, 2019 and 2022, all station types

Year	Pollutant	Number of stations (data availability of daily values)	1h max/24h or 1h max/8h max. for O_3	1h P95/24h or 1h P95/8h max. for O_3	1h P90/24h or 1h P90/8h max. for O_3	1h P70/24h or 1h P70/8h max. for O_3
2019	$PM_{2.5}$	218 (96 %)	**1.86**	1.65	1.51	1.16
	PM_{10}	361 (98 %)	**1.86**	1.62	1.48	1.15
	O_3	272 (98 %)	**1.13**	1.08	1.04	0.87
	NO_2	411 (99 %)	**1.97**	1.73	1.57	1.17
	SO_2	115 (91 %)	**2.2**	1.72	1.46	1.04
2022	$PM_{2.5}$	286 (97 %)	**1.78**	1.58	1.45	1.14
	PM_{10}	361 (98 %)	**1.79**	1.56	1.44	1.14
	O_3	277 (97 %)	**1.12**	1.07	1.04	0.88
	NO_2	409 (98 %)	**2.01**	1.76	1.58	1.17
	SO_2	108 (94 %)	**2.05**	1.63	1.4	1.04

The transformation factors used for the further calculations are shown in bold.

6.1.3 Transformation of the effect estimates

The effect estimates based on the 24-hour mean values were divided by the transformation factor (Table 7) as per Figure 3. For O_3, the effect estimate based on the 8-hour mean values was divided by the O_3 transformation factor. Table 8 shows the calculated 1-hour effect estimates per

10 µg/m^3 of the 1-hour maximum value as a percentage increase in the number of cases of disease.

The 1-hour effect estimates were used to compare the health effects of pollutants on an hourly basis. However, the 1-hour effect estimate must not be interpreted as a relative risk for a one-hour exposure period as it does not refer to the biological effect of a one-hour exposure period but to the 1-hour maximum of a 24-hour period. In other words, an hourly value is taken as the maximum value for a whole day.

Table 8: 1-hour effect estimate (additional cases in per cent) per 10 µg/m³ concentration increase

Pollutant	Hospital admissions for cardiovascular diseases in %	Hospital admissions for respiratory diseases in %	ER visits or hospital admissions for asthma in %	Excess mortality in %
$PM_{2.5}$ (1h)	0.55	0.77	1.59	0.38
PM_{10} (1h)	0.38	0.88	0.55	0.22
O_3 (1h)	Na[1]	0.18	0.27	0.36
NO_2 (1h)	Na	0.90	0.70	0.35
SO_2 (1h)	Na	Keine Daten	0.47	0.28

[1] N/A – not applicable because the evidence for an association is not considered to be at least likely causal.

6.1.4 Alternative approach

As an alternative to this approach, it would have been possible to use effect estimates for health effects from studies on surrogate outcomes, such as blood pressure increase, increase in inflammatory markers in the blood or lungs, decrease in lung function, etc. In the panel studies that are typically used to analyse these endpoints, data is usually available at the highest possible temporal resolution ranging from minutes to hours. The relative effects of one-hour exposures could thus be used as a basis for the UBA AQI. However, this approach was rejected because these studies often examine very highly selected study participants (e.g. those with pre-existing conditions such as asthma, high blood pressure, etc.) and are very small compared to time series analyses. Furthermore, the significance of a possibly acute and transient change in these surrogate outcomes for hospital admissions, ER visits and mortality, and thus for public health, is uncertain.

7 Step 5: Standardization of the pollutant effects to $PM_{2.5}$ as a reference pollutant

7.1 Rationale

A key component of the risk-based index is the calculation of so-called equivalence coefficients, which are used to express the health impacts of the pollutant concentrations in each index category on an equivalent level.

$PM_{2.5}$ was chosen as the reference pollutant for several reasons: the highest number of studies is available for $PM_{2.5}$ (WHO AQG 2021); the $PM_{2.5}$ effect estimates for the selected outcomes have the narrowest confidence intervals; $PM_{2.5}$ causes the strongest health effects per unit of mass (e.g. $\mu g/m^3$) compared to the other regulated pollutants in most studies (WHO AQG 2021) and also causes the greatest disease burden in Europe (European Environment Agency 2024).

7.1.1 Equivalence coefficients, meaning and calculation

The aim of this step is to determine the health impacts of the pollutants included in the index in relation to the effect of $PM_{2.5}$. This relative health impact of air pollutants compared to $PM_{2.5}$ is called the equivalence coefficient; it is the value by which the respective pollutant concentration must be multiplied to achieve the same risk increase per outcome as with a $10 \mu g/m^3$ increase in $PM_{2.5}$ concentration.

The equivalence coefficients per pollutant and per endpoint can be determined using a standard procedure by dividing the 1-hour effect estimate for $PM_{2.5}$ (Table 8) by the 1-hour effect estimate of the other pollutant for the same outcome (Figure 5):

Figure 5: Equation equivalence coefficient

$$\text{Equivalence coefficient} = \frac{\text{1-hour effect estimate for } PM_{2.5}}{\text{1-hour effect estimate for air pollutant X}}$$

Source: Own representation, Institute for Occupational, Social and Environmental Medicine, Environmental Epidemiology Working Group, University Hospital Düsseldorf, Heinrich Heine University Düsseldorf.

The effect estimates are shown in Table 8. The equivalence coefficients for the selected exposure-outcome pairs are shown in Table 9 as central point estimates (i.e. without confidence intervals) for the 1-hour effect estimate.

Table 9: Equivalence coefficients per pollutant and outcome per 10 µg/m³ concentration increase

	Equivalence coefficients			
Pollutant	Hospital admissions for cardiovascular diseases	Pollutant	Hospital admissions for cardiovascular diseases	Pollutant
$PM_{2.5}$ (1h)	1.00	1.00	1.00	1.00
PM_{10} (1h)	1.43	0.88	2.91	1.75
O_3 (1h)	-	4.33	5.98	1.08
NO_2 (1h)	-	0.96	2.26	1.09
SO_2 (1h)	-	-	3.39	1.36

7.1.2 Aggregation of the equivalence coefficients per pollutant

Applying the equation of the equivalence coefficient (Figure 5) to all pollutants yields an equivalence coefficient for each exposure-outcome pair (Table 9). That is, there are between four (PM_{10}) and two (SO_2) equivalence coefficients per pollutant, depending on the respective number of endpoints selected in step 1. However, a single equivalence coefficient per pollutant must be used for the index.

Furthermore, the equivalence coefficients based on the point estimates of the effect sizes (i.e. derived from the central effect estimates without taking into account the confidence intervals) do not reflect the degree of uncertainty of the relative health effects. These central values for the equivalence coefficients are sensitive to small changes in the original effect estimates of the epidemiological studies. Any new publication or change in the literature in the field of air quality effects research could lead to (most likely small) changes in the central equivalence coefficients.

The point estimates are pseudo-precise since the true (relative) health effects are distributed over a wide range and cannot be adequately characterised by a single central value. Instead, the equivalence coefficients should allow for an average comparison of the health effects of the various pollutants, with the degree of uncertainty made transparent.

To derive one robust equivalence coefficient per pollutant, taking into account and reporting the statistical uncertainty, a simulation was carried out using the confidence intervals of the original epidemiological 24-hour effect estimates. This technique helps form a sense of the true distribution around the point estimates and serves to aggregate the equivalence coefficients per pollutant. It also accounts for and displays the inherent uncertainty in the statistical estimation of the epidemiological effect sizes.

Furthermore, weighting techniques were examined for their suitability to calculate a single equivalence coefficient per pollutant. This alternative method is explained in Appendix A.1. It has advantages for evaluating the relevance of a health endpoint in the population but does not provide any individual assessment options and is therefore not used to derive the equivalence coefficients as part of this method.

7.1.2.1 Simulation methodology

A random number simulation was carried out to estimate the variability and the range of uncertainty of the individual equivalence coefficients and to show the full range of values the equivalence coefficients can take. Assuming a normal distribution for the 24-hour and 8-hour effect estimates, their respective distribution parameters (mean and standard deviation) were calculated based on the point estimates and the confidence intervals for each exposure-outcome pair (Table 10); 10,000 simulations per exposure-outcome pair were performed using these distributions. As a result, 10,000 normally distributed random values were generated for each exposure-outcome pair. These random 24-hour and 8-hour effect estimates were then converted into 1-hour effect estimates based on the transformation factors described above. In the next step, equivalence coefficients were calculated for each random value. For this purpose, a randomly drawn value from the distribution of the 1-hour effect estimate for $PM_{2.5}$ was divided by a randomly drawn value from the distribution of the 1-hour effect estimate for the other pollutant. As a result, we obtained 10,000 equivalence coefficients per pollutant per outcome.

Combining the distributions from the simulations for all selected outcomes of a pollutant allowed for the creation of an integrated distribution of equivalence coefficients for each pollutant. This distribution shows the spread of a pollutant's relative health impacts, expressed as equivalence coefficients, compared to $PM_{2.5}$. The central measures of the distribution (mean, median and mode) indicate which equivalence coefficients are most consistent with the current evidence. The mode was selected as the equivalence coefficient for the further development of the UBA AQI, barring compelling reasons for using a different approach. Pragmatic decisions were made for NO_2 and O_3, which are explained in the course of this report.

Table 10: Point estimates and 95% confidence intervals of the relative risks as additional cases in per cent for short-term pollution (24-hour or 8-hour mean values) per 10 µg/m³ concentration increase and the characteristic values of the simulation distribution

Pollutant	Endpoint	Relative risks (CI 95%)	Mean value and standard deviation in simulations
$PM_{2.5}$	Hospital admissions for cardiovascular diseases	1 (0.6; 1.4)	1 (0.2)
$PM_{2.5}$	Hospital admissions for respiratory diseases	1.4 (1.0; 1.7)	1.4 (0.18)
$PM_{2.5}$	ER visits or hospital admissions for asthma	2.9 (1.7; 4.1)	2.9 (0.61)
PM_{10}	Hospital admissions for cardiovascular diseases	0.7 (0.2; 1.1)	0.69 (0.24)
PM_{10}	Hospital admissions for respiratory diseases	1.6 (0.0; 3.1)	1.6 (0.79)
PM_{10}	ER visits or hospital admissions for asthma	1 (0.8; 1.3)	1 (0.13)
O_3	Hospital admissions for respiratory diseases	0.2 (-0.2; 0.5)	0.2 (0.18)
O_3	ER visits or hospital admissions for asthma	0.3 (-0.7; 1.5)	0.3 (0.56)
NO_2	Hospital admissions for respiratory diseases	1.8 (1.1; 2.5)	1.8 (0.33)
NO_2	ER visits or hospital admissions for asthma	1.4 (0.8; 2)	1.4 (0.31)
SO_2	ER visits or hospital admissions for asthma	1 (0.1; 2)	1 (0.48)
$PM_{2.5}$	All-cause mortality	0.7 (0.4; 0.9)	0.7 (0.13)
PM_{10}	All-cause mortality	0.4 (0.3; 0.5)	0.4 (0.05)
O_3	All-cause mortality	0.4 (0.3; 0.5)	0.4 (0.05)
NO_2	All-cause mortality	0.7 (0.6; 0.9)	0.7 (0.08)
SO_2	All-cause mortality	0.6 (0.5; 0.7)	0.6 (0.05)

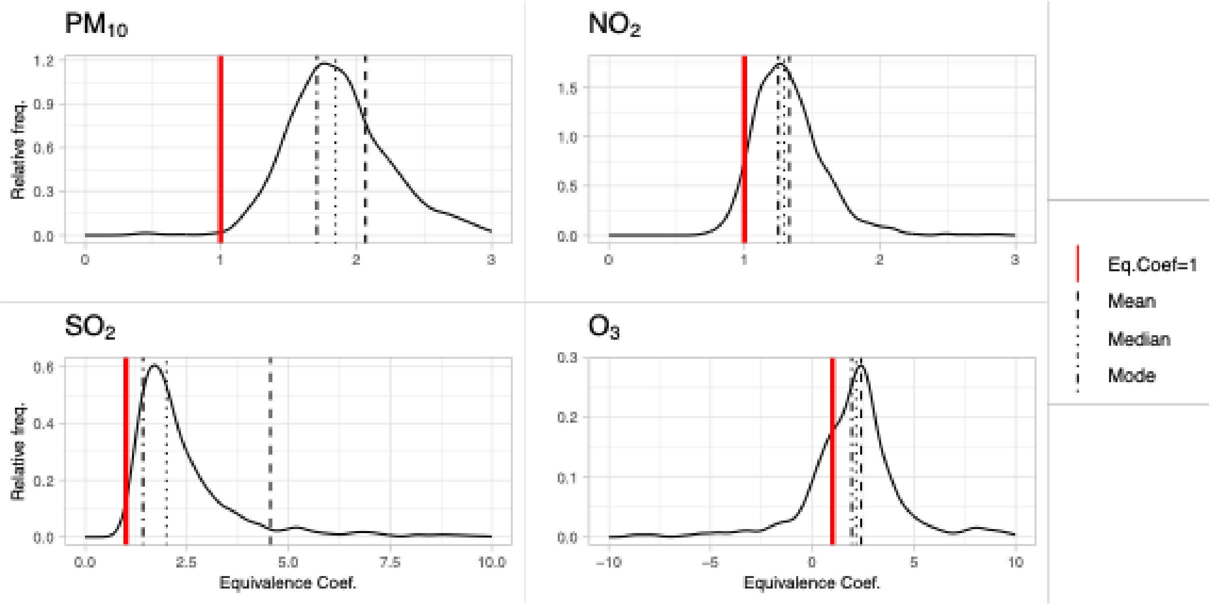
7.1.3 Simulation results

Table 11 shows the mean, median and mode values and the uncertainty in the form of 95% uncertainty ranges of the equivalence coefficients per pollutant. The term “uncertainty ranges” is used instead of “confidence intervals” because the results are based on a simulation and do not represent the effect estimates from the primary epidemiological studies. The distributions are represented graphically in Figure 6.

Table 11: Statistical parameters of the simulated equivalence coefficients (n = 10,000).

Pollutant	Mean	Median	Mode	95% uncertainty range	Adjusted equivalence coefficients
NO_2	1.46	1.42	1.44	[1.01; 2.12]	2.00
O_3	1.00	2.33	2.31	[-27.18; 30.43]	4.80
PM_{10}	1.97	1.84	1.75	[1.19; 3.42]	1.80
SO_2	2.79	2.34	1.99	[1.15; 10.15]	2.00

Figure 6: Distribution of the simulated equivalence coefficients (n = 10000).



Source: Own representation, Institute for Occupational, Social and Environmental Medicine, Environmental Epidemiology Working Group, University Hospital Düsseldorf, Heinrich Heine University Düsseldorf.

7.1.4 Plausibility check and final definition of equivalence coefficients by experts

For the final definition of the equivalence coefficients used in the index, these data-based calculations (simulation and representation of the central tendency) were complemented by the specialist knowledge of experts in the field of environmental epidemiology, as well as that of the project team and experts at the UBA, in order to account for additional aspects of the epidemiological data.

For PM_{10}, the modal value of the calculated distributions of the equivalence coefficients is 1.75, with an uncertainty range of 1.19 to 3.42. The modal value of 1.75 approximates the simple mean of the equivalence coefficients of all examined outcomes (Table 11). Furthermore, it approximates the mass ratio of $PM_{2.5}$ and PM_{10} as well as the ratio of the effect estimates from the original epidemiological studies; it is thus plausible in terms of comparable particulate matter characteristics of these size categories. Therefore, an equivalence coefficient of 1.8 was set (rounded to the first decimal place).

For SO_2, the modal value of the calculated distributions of the equivalence coefficients is 1.99, with a right-skewed distribution and an uncertainty range of 1.15 to 10.15. The modal value of 1.99 approximates the simple mean of the equivalence coefficients (Table 10) and the ratio of effect estimates from the epidemiological studies. It is therefore plausible, and an equivalence coefficient of 2.0 was set.

For NO_2, the modal, mean and median values were 1.4 with an uncertainty range of 1.01 to 2.12. This distribution of equivalence coefficients does not take into account that NO_2 and $PM_{2.5}$ often come from the same sources in the epidemiological studies and are therefore correlated. This can lead to a blurring of the effects (so-called confounding). Confounding complicates the attribution of effects to pollutants; studies that account for the confounding by statistical measures (e.g. by adjustment) show that the effects of NO_2 are often overestimated. In many of the original studies on NO_2, the effect estimates for NO_2, are not adjusted for $PM_{2.5}$ or PM_{10}, which may result in an upward distortion of the estimated relative risks. The European Environment Agency and Public Health England usually assume an overestimation of about 30% in their assessments of the long-term effects of NO_2 and state that the effect estimates for NO_2 should be corrected downwards accordingly (European Environment Agency 2021; Committee on the Medical Effects of Air Pollution 2014). As for short-term effects, some studies have shown that the association between NO_2 and mortality can also be significantly affected by other pollutants, and that adjusting for the effect of these substances reduces the estimated effect by up to 50%, depending on the pollutant (Samoli et al. 2006; Ma et al. 2024). For this reason, the equivalence coefficient was corrected by a factor of approximately 30% and set to a value of 2.0. This corresponds to the WHO AQG 2021 ratio for long-term levels of NO_2 (10 $\mu g/m^3$) and $PM_{2.5}$ (5 $\mu g/m^3$). The ratio of the 24-hour mean values for NO_2 (25 $\mu g/m^3$) and $PM_{2.5}$ (15 $\mu g/m^3$) is 1.7 and is thus similar.

The modal value for O_3 was 2.31 with an uncertainty range of -27.18 to 30.43. This large uncertainty range is primarily due to the small effect size and the wide confidence interval of the effect estimate of O_3. That wide confidence interval is due to the small number of epidemiological studies conducted in temperate regions and the heterogeneity of the effect estimates for mortality and morbidity. It was therefore decided to prioritize the morbidity endpoints over mortality when determining the equivalence coefficient. The point estimates for the equivalence coefficients were 6.18 for hospital admissions for all respiratory diseases and 5.98 for the subgroup of asthmatic diseases. The equivalence coefficient was therefore set to 4.8 in order to simultaneously match the highest index threshold for O_3 to the alert threshold of the EU Ambient Air Quality Directive (Europäische Kommission 2022).

It should be noted that the lower interval limits of the simulated equivalence coefficient for O_3 are negative, which is due to the partially negative lower category thresholds of the original confidence intervals for O_3 in the meta-analyses performed. Since only studies from regions with a temperate climate were used to determine the relative risk, the confidence intervals of the meta-analyses are significantly larger than in the original reviews, which include all studies. Thus, the present analysis shows a lower precision for the relative risk of O_3 than can be found in the literature overall. To apply the present methodology in Europe, it would be useful to conduct the calculations for the O_3 equivalence coefficient with all studies, so as to incorporate findings from the Mediterranean region as well. This would also increase the precision of the estimate of the equivalence coefficient.

7.1.5 Sensitivity analyses

Using post hoc sensitivity analyses, we calculated which equivalence coefficients could be used to represent the alert and information thresholds set out in the trilogue agreement on the Air Quality Directive. The results are described below. These equivalence coefficients, determined post hoc, could be used in a possible adjustment of the index to new alert and information thresholds.

Further sensitivity analyses included a variation of the calculation of the transformation factor for the conversion of 24-hour mean values to 1-hour mean values (different time periods, different indicators (95%, 90%, 70%)), the inclusion of additional health outcomes or restriction to a smaller number of health endpoints for the calculation of the equivalence coefficients, updated data incorporating results from new reviews published during the project period, the use of different thresholds for the upper category bound and the use of different delayed exposure periods (so-called lags) in the primary studies. Overall, the equivalence coefficients proved to be highly robust to variations in the input variables.

7.1.6 Adjustment of equivalence coefficients to alert and information thresholds

Based on the information and alert thresholds proposed by the EU, we calculated the equivalence coefficients which would put the threshold between the “poor” and “very poor” categories at either the information threshold or the alert threshold. The information and alert thresholds were taken from the trilogue agreement on the Directive of the European Parliament and the Council on ambient air quality and cleaner air for Europe (EU-Parlament 2024). It should be noted that the different averaging times for the index were not taken into account. The information and alarm thresholds as well as the calculated equivalence coefficients are shown in Table 12.

Table 12: Information and alert thresholds from the trilogue agreement and adjusted equivalence coefficients (EU-Parlament 2024)

Pollutant	Equivalent coefficient used	Information threshold, µg/m³ *	Equivalence coefficient at which the category threshold between “poor” and “very poor” corresponds to the information threshold	Alert threshold, µg/m³ *	Equivalence coefficient at which the category threshold between “poor” and “very poor” corresponds to the alert threshold
$PM_{2.5}$	1	50	1	50	1
PM_{10}	1.80	90	1.80	90	1.80
O_3	4.80	180	3.60	240	4.80
NO_2	2.00	150	3.00	200	4.00
SO_2	2.00	275	5.50	350	7.00

* The data assessed based on the information thresholds is measured over periods of 1 hour for SO_2, NO_2 and O_3 and 1 day for PM_{10} and $PM_{2.5}$ at locations representative of air quality in an area of at least 100 km² or an entire zone, whichever is smaller.

** The data assessed based on the alert thresholds is measured as an hourly average over three consecutive hours for SO_2, NO_2 and O_3 and as a daily average over three consecutive days for PM_{10} and $PM_{2.5}$ at locations representative of air quality in an area of at least 100 km² or an entire zone, whichever is smaller.

8 Step 6: Definition of the category thresholds of the AQI for $PM_{2.5}$

8.1 Rationale for the five proposed categories of the AQI.

It is difficult to derive evidence-based category thresholds for linear exposure-response relationships, such as those that apply approximately to the air pollutants considered here and the air pollutant concentrations found in Germany. Any increase in concentration leads to an increase in risk, and there are no biologically justifiable threshold values that indicate a distinct risk shift. Every category threshold is therefore subject to the criticism of being somewhat arbitrary. In order to nevertheless base the determination of the category thresholds on scientifically derived and verifiable data, it was decided to use the annual level recommended from the WHO AQG 2021 for $PM_{2.5}$ and the information and alert thresholds of the EC Draft 2022 as a starting point. This means that the category thresholds are set in a normative way. $PM_{2.5}$ was treated as the primary pollutant since it is the pollutant for which the most evidence of health effects is available.

8.1.1 Category threshold very good – good

The WHO AQG 2021 level for the annual mean of $PM_{2.5}$ (5 µg/m^3) is used as the threshold between “very good” and “good”. The rationale for this is that if this value is adhered to, the risk of developing chronic health effects is very small.

8.1.2 Category threshold good – moderate

The WHO AQG 2021 level for the daily mean of $PM_{2.5}$ (15 µg/m^3) is used as the threshold between “good” and “moderate”. The reason is that, according to WHO recommendations, this value ensures that the risk of short-term health effects is low.

8.1.3 Category threshold moderate – poor

The WHO AQG 2021 level of 15 µg/m^3 for the daily mean value of $PM_{2.5}$ is transformed into an hourly mean as the upper bound of the “moderate” category (bordering on “poor”). The transformation factor of 2, calculated in step 4, is used to this end; the calculated 1-hour daily maximum value is thus 30 µg/m^3 (15 µg/m^3 x 2). According to the definition of the levels, there is an increased risk of serious health effects between daily mean values of 15 and 30 µg/m^3 of $PM_{2.5}$ (WHO AQG 2021), which justifies a classification as “moderate”.

8.1.4 Category threshold poor – very poor

The information threshold of the EC Draft 2022 and the trilogue agreement for the daily mean value of $PM_{2.5}$ (50 µg/m^3) is used to determine the boundary between “poor” and “very poor” (Europäische Kommission 2022; EU-Parlament 2024). This information threshold value was adopted unchanged for the index and not converted into an hourly value. Furthermore, the different averaging time for $PM_{2.5}$ is not taken into account here.

The interim targets set by the WHO AQG 2021 could be used as an alternative to the statutory alarm or information thresholds. However, like the statutory limit values, they are not health-based but intended to provide guidance to countries with significantly higher levels of air pollution when formulating air pollution control programs.

9 Step 7: Application of the $PM_{2.5}$ category thresholds to the other pollutants

After determining the category thresholds for $PM_{2.5}$, the category thresholds for the other pollutants were determined using the equivalence coefficients (Table 13). To this end, the $PM_{2.5}$ category thresholds were multiplied by the equivalence coefficients for the respective pollutants. The aim of this approach is to derive pollutant categories for which the risk increases of the individual pollutants are on average comparable to the risk increase of $PM_{2.5}$ in this category across many health endpoints.

Table 13: Risk-based UBA AQI, including category thresholds and equivalence coefficients

Index	**Hourly mean values in µg/m³**									
	NO_2		**PM_{10}**		**$PM_{2.5}$**		**O_3**		**SO_2**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Very poor	101		91		**51**		241		101	
Poor	61	100	55	90	**31**	**50**	145	240	61	100
Moderate	31	60	28	54	**16**	**30**	73	144	31	60
Good	11	30	10	27	**6**	**15**	25	72	11	30
Very good	0	10	0	9	**0**	**5**	0	24	0	10
Equivalence coefficient	2.00		1.80		1.00		4.80		2.00	

9.1 Interaction module

Rather than affecting human health in isolation, air pollutants usually occur in the form of various mixtures, resulting in multiple exposures. This can lead to an additive, a synergistic and sometimes a weakening interaction (Mauderly und Samet 2009; Li et al. 2023). In an index, these interactions due to multiple exposures can be incorporated in different ways.

A literature search on interactions conducted as part of the UBA AQI development included some original studies but no reviews on interactions for the exposure-outcome pairs considered here. For example, an original paper examining the interaction of $PM_{2.5}$ and O_3 on hospital admissions for respiratory diseases found indications of a synergistic effect (Li et al. 2023). A non-systematic review (Mauderly und Samet 2009) also confirmed the existence of synergistic effects of air pollutants in triggering measurable biological responses, as demonstrated in human and animal laboratory studies.

Despite the lack of exact quantitative estimates for the interactions and the associated risk increases, it makes sense to take multiple exposures into account when considering preventive public health measures. So far, this risk increase is only communicated qualitatively in the UBA AQI in the UBA app or on the UBA website, e.g. by the following text in the behavioural recommendations for a pollutant: “In combination with other air pollutants, also less sensitive people may react to this air pollution.”

In order to better represent the interactions in the index, and above all not to leave their consideration to the users, an optional interaction module was developed based on the methodology of the Dutch AQI (Dusseldorp et al. 2014). In this interaction module, an additional risk increase is qualitatively taken into account if at least two pollutants are in categories associated with increased health risk ("moderate" to "very poor").

The interaction module developed here accounts for interactions qualitatively, using specific rules to determine the overall index by incorporating the concentrations of multiple air pollutants. The following rules are applied:

- If the highest category among all pollutants is "moderate", with at least two pollutants in this category and both concentrations in the upper 50% of the category, the overall index is shifted into the "poor" category.
- If the highest category among all pollutants is "poor", with at least two pollutants in this category and both concentrations in the upper 50% of the category, the overall index is shifted into the "very poor" category.

The relevant combinations of air pollutants for this assessment are

- $PM_{2.5}$ or PM_{10} and NO_2,
- $PM_{2.5}$ or PM_{10} and O_3,
- $PM_{2.5}$ or PM_{10} and SO_2,
- O_3 and NO_2,
- NO_2 and SO_2,
- O_3 and SO_2.

These rules allow multiple exposures and their synergistic health effects to be taken into account, which in turn enables a more comprehensive assessment of the health significance of increased pollutant concentrations.

Some examples are shown in the tables below. Table 14 defines the overall index as "poor", even though all pollutants but one fall into the categories "very good" and "good" (NO_2 falls into the category "poor"). In Table 15, the highest value for a single pollutant is "moderate", as determined by NO_2 and $PM_{2.5}$. Although the $PM_{2.5}$ concentration is in the upper half of the "moderate" category, the NO_2 concentration is in the lower half, meaning that the overall index value is not increased. Table 16 shows a different situation. Both $PM_{2.5}$ and NO_2 are in the upper half of the "moderate" category, so that the overall index is downgraded to "poor".

Table 14: Example 1 for the application of the interaction module algorithm.

Pollutant	Category	Overall index
NO_2	**Poor**	**Poor**
PM_{10}	**Good**	
$PM_{2.5}$	**Good**	
O_3	**Good**	
SO_2	**Very good**	

Table 15: Example 2 for the application of the interaction module algorithm.

Pollutant	Category	Overall index
NO_2	Moderate (<50%)	Moderate
PM_{10}	Good	
$PM_{2.5}$	Moderate (>50%)	
O_3	Good	
SO_2	Very good	

Table 16: Example 3 for the application of the interaction module algorithm.

Pollutant	Category	Overall index
NO_2	Moderate (>50%)	Poor
PM_{10}	Good	
$PM_{2.5}$	Moderate (>50%)	
O_3	Good	
SO_2	Very good	

10 Derivation of health recommendations

Based on the updated category thresholds and the resulting assessment categories of the UBA AQI, health-related behavioural recommendations were developed along with corresponding explanations. The behavioural recommendations are differentiated according to sensitivity to the effects of air pollutants (general population and sensitive groups such as individuals with pre-existing conditions, old or very young individuals, pregnant women). Since the assessment categories for the individual pollutants show comparable risk increases for short-term health endpoints, it was not necessary to formulate behavioural recommendations for individual pollutants. Due to the intended use of the index for short-term behavioural adjustment, the recommendations focus on short-term effects, although long-term effects, concentrations and the spatial characteristics of pollution measurements are addressed as well. For successful communication, aspects such as comprehensibility of language, brevity and conciseness of formulations, clarity/unambiguity and feasibility/relevance of recommendations are also taken into account.

The strategy for deriving behavioural recommendations was based on the following initial situation:

- The assessment was to be based on the most recent hourly data in order to achieve short-term behavioural changes to prevent short-term adverse health effects.
- Short-term exposure to air pollutants primarily affects particularly sensitive groups (individuals with pre-existing conditions, old or very young individuals, pregnant women) – for example, short-term inhalation studies show that NO2 in individuals with mild asthma showed a measurable decrease in forced lung volumes with increasing pollutant concentrations, similar to those found at the side of busy roads (US EPA 2024a, S. 5-253 - 5-257), while no consistent effects were found in healthy adults (US EPA 2024b, S. 5-89 - 5-92; Kapitel 5.1.7.2).
- Most indices that include health recommendations address the level of physical activity, which is one of the most important and strongest individual health protection factors (Barrera et al. 2023; World Health Organization 2018; Nazelle et al. 2011). This applies to almost all surrogate endpoints and risk factors for chronic diseases, as well as to manifest clinical outcomes such as cardiovascular diseases, diabetes, dementia etc. (Castro et al. 2023). However, as the promotion of physical activity through behavioural and structural measures is becoming ever more important in our increasingly sedentary society, care was taken not to generally discourage the population from engaging in outdoor physical activity in developing the UBA AQI health recommendations.
- Active mobility (walking, cycling, public transport use) is one of the most important elements of the transport and climate transition and can significantly improve air quality in cities (Brand et al. 2021). The population can therefore contribute to improving air quality; public awareness of this issue is to be raised by providing information on low-emission behaviour.

Based on these framework conditions, general information on increased risk as well as health-related behavioural recommendations and advice on reducing emissions were provided. The general information contains statements regarding air quality, increased risk and the population groups affected. The health-related behavioural recommendations were subdivided into recommendations for particularly sensitive groups and for the general population. Within this structure, particularly sensitive groups are advised to monitor their symptoms and to shift or reduce their physical activity in lower assessment categories than the general public. The other behavioural recommendations provide general advice on how to avoid or reduce emissions, particularly with regard to transport, heating and the use of combustion engines outside the transport sector.

A Proposal to behavioural recommendations for the new AQI is shown in table Table 17.

Table 17: Proposed behavioural recommendations for the new AQI

Index	Risk	Health-related behaviour		Other behavioural recommendations[1]
	General information	General public	Particularly sensitive groups	
Very poor	The current air quality is very poor. Health issues may arise. Individuals with pre-existing lung and cardiovascular diseases, children and the elderly are most at risk, but even healthy people may experience health effects.	Postpone physically demanding activities or relocate them to places with better air quality. If you experience health effects such as coughing or shortness of breath, you should reduce your physical activity.	Avoid physical exertion outdoors. Postpone physically demanding activities or relocate them to places with better air quality. If you experience any health effects such as coughing or shortness of breath, you should stop your physical activity and review your medication with your doctor.	You can help to ensure that air pollution stops rising and starts falling by leaving your car at home. Use public transport and walk or cycle shorter distances. Form carpool instead of driving alone. Do not burn wood in stoves or fireplaces and refrain from lighting any kind of fire outdoors. Do not use any equipment with combustion engines for hobbies or garden work.
Poor	The current air quality is poor. Health issues may arise. Individuals with pre-existing lung and cardiovascular diseases, children and the elderly are most at risk.	If you exercise outdoors, you should choose an area with better air quality (e.g. low traffic). If you experience health effects such as coughing or shortness of breath, you should reduce your physical activity.	Postpone physically demanding activities or relocate them to places with better air quality. Alternatively, reduce the level of your physical exertion. If you experience any health effects such as coughing or shortness of breath, you should stop your physical activity and review your medication with your doctor.	
Mäßig	The current air quality is moderate. Particularly sensitive people may	Enjoy your usual outdoor activities.	If you exercise outdoors, you should choose an	You can help to ensure that air pollution does not rise or starts falling

Index	Risk	Health-related behaviour		
	General information	**General public**	**Particularly sensitive groups**	**Other behavioural recommendations[1]**
	experience health problems. Individuals with pre-existing lung and cardiovascular diseases are most at risk.		area with better air quality (e.g. low traffic) and pay attention to possible health effects. If you repeatedly experience health effects such as coughing or shortness of breath, you should reduce your physical activity and review your medication with your doctor.	by leaving your car at home. Use public transport and walk or cycle shorter distances. Form carpool instead of driving alone. If possible, do not use any equipment with combustion engines for hobbies or garden work.
Good	The current level of air pollution is low. Short-term health problems due to air pollution are unlikely. However, effects on chronic diseases cannot be ruled out in the event of long-term exposure at this level.	Enjoy your outdoor activities.	Enjoy your outdoor activities.	You can help keep the air pollution low by leaving your car at home, using public transport and walking or cycling shorter distances. Form carpool instead of driving alone.
Very good	The current level of air pollution is very low. No health problems are expected to be caused by air pollutants.	Enjoy your outdoor activities.	Enjoy your outdoor activities.	If possible, do not use any equipment with combustion engines for hobbies or garden work.

[1] The advice for “Other behavioural recommendations” was largely adopted from the Swiss air quality index and the WHO recommendations for the design of air quality indices (König Minger et al. 2020; WHO 2023)

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A.1 Appendix

A.1.1 Alternative calculation of the equivalence coefficient

An alternative method for calculating equivalence coefficients for pollutants using a weighted average was examined. The weights were determined based on the proportion of selected health conditions in the German hospital admission statistics. Mortality was excluded from the calculation due to the inherent lack of comparability with morbidity outcomes and the complexity of distinguishing between death, death during hospitalisation and hospitalisation with discharge diagnoses.

The weight calculations were derived from the official hospital statistics of the Federal Statistical Office (Federal Statistical Office 2023). In 2022, there were 2,537,301 hospitalisations for cardiovascular diseases (ICD-10 diagnoses I00-I99) and 1,130,202 hospitalisations for respiratory diseases (ICD-10 diagnoses J00-J99). Looking only at these two results, their relative share was 69.2% and 30.8% respectively. ER visits or hospital admissions for asthma accounted for only 0.6% of all admissions and 9% of hospital admissions for respiratory diseases (European Respiratory Society 2023). After including asthma in the list of outcomes, the weights were adjusted to 69.2% for hospitalisations for cardiovascular diseases, 28.2% for hospitalisations for respiratory diseases and 2.6% for ER visits or hospitalisations for asthma. These weights were then multiplied by the equivalence coefficient per pollutant for each outcome, resulting in a weighted average across all endpoints.

The application of these weights to the equivalence coefficient resulted in significantly higher coefficients for NO_2, SO_2 and O_3 compared to PM_{10}. The reason for this is that there is no confirmed link between these pollutants and cardiovascular diseases, and respiratory diseases are much less common than cardiovascular diseases. For example, pollutants such as SO_2, for which a causal link has only been demonstrated with asthma, play a relatively minor role in the health system as a whole due to the low prevalence of asthma. With weighting, the equivalence coefficient calculated is 53.77, whereas the equivalence coefficient for PM_{10} is 1.7. This can be interpreted to mean that SO_2 is 54 times less important for the healthcare system than $PM_{2.5}$, since the relative rate of hospital admissions for asthma is low compared to hospital admissions for cardiovascular diseases.

This approach reflects the prevalence of certain diseases within the population, emphasises a population-based perspective and highlights the significance of the results for the healthcare system rather than for the individuals exposed. Although it can be useful for the allocation of healthcare resources, we do not consider this approach appropriate for use in an index that is intended to make recommendations on individual behaviour. Therefore, this method of deriving pollutant-specific equivalence coefficients was not incorporated into the UBA AQI calculation.