CLINSH

RELIABLE WATERWAY TRANSPORT, FRESH AIR

Modelling, Evaluating and scenario building

Deliverable B4

CLEAN INLAND SHIPPING

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Project: CLINSH – Clean Inland Shipping

Goal: The objective of LIFE CLINSH is to improve air quality in urban areas situated close to ports and inland waterways, by accelerating IWT emission reductions.

Project reference: LIFE15 ENV/NL/000217

Duration: 2016 – 2021

Project website: www.clinsh.eu

CLINSH is an EC LIFE+ project delivered with the contribution of the LIFE financial instrument of the European Community. Project number LIFE15 ENV/NL/000217

This deliverable is part of Action B4 modelling, evaluating and scenario building.

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Version: 1.0

Date: 14/10/2021

Glossary

Abbreviation	Meaning
CLINSH	Clean Inland Shipping project under LIFE+ programme
CO2-eq	Carbon dioxide equivalent
DPF	Diesel particulate filter, to reduce particulate emissions
dwt	Deadweight tonnage: the total mass a shipping vessel can carry (load, fuel, ballast water), expressed in tonnes
FWE	Fuel water emulsion
GTL	Gas-to-Liquids, a synthetic diesel oil made from natural gas
HVO	Hydrotreated Vegetable Oil
IWT	Inland waterway transport
kW	Kilowatt
kWh	Kilowatt-hour
kton	Kiloton
LNG	Liquefied Natural Gas
MJ	Megajoule
NOx	Collective term for mono-nitrogen oxides (NO, NO_2 and NO_3), emissions which lead to smog formation, environmental acidification and respiratory damage
PV	Passenger vessel
PB	Push boat
PM	Particulate matter
PM2.5	Particulate Matter smaller than 2.5 micro-metre
PM10	Particulate Matter smaller than 10 micro-metre
ppm	Parts per million
SCR	Selective Catalytic Reduction, an exhaust gas treatment system to reduce NO_x emissions
Stage IIIa, IV, V	European emission standards for non-road mobile machinery (NRMM), such as construction equipment, railroad engines, inland waterway vessels, and off-road recreational vehicles. (Regulations: 2004/26/EC, (EU) 2016/1628)
TEU	Standard shipping container size expressing container volume: Twenty-feet

Summary

The key objective of Action B4 is a sub-objective of the Clinsh project: *Demonstrate the effect of different scenario's on air quality by using high resolution modelling.* To estimate the impact of inland shipping on air quality measuring of air pollutants concentrations and modelling is required.
The CLINSH measurement programme in Bimmen-Lobith ran from April 2016 until December 2020. The impact of ship emissions (approx. 110,000 ship passages per year) could be estimated quite well using the measurements. The wind at the German-Dutch border comes predominantly from westerly directions, so it is to be expected that the ship exhaust gases predominantly have an effect on the right, easterly bank of the Rhine. On the left bank of the Rhine, the NO_2 concentrations measured were 1- 2µg/m³ higher compared to the local background concentrations On the easterly bank, the NO_2 concentrations measured were 3-5µg/m³ higher compared to the local background concentrations. It can be assumed that the higher concentrations are the direct effects of the approximately 110,000 annual inland waterway vessel passages.

With more than 16,000 measuring results, it was possible to compile a catalogue of onshore emission factors for inland vessels on the Lower Rhine, classified according to vessel size, direction of travel (upstream/downstream) and speed over ground. With this catalogue and the recording of real ship traffic, a new method for determining the emissions of moving ships was developed and applied for the study area Neuss-Duisburg within the framework of CLINSH. The emission data is no longer based on estimates of theoretical diesel consumption from performance/emission curves but on measured (real life) onshore data.

The LANUV NRW investigated the air pollution with NO_2 in Duisburg, the largest inland port in Europe, as well as in Neuss/Düsseldorf, which is another large inland port, for the CLINSH-project in 2018 with very dense measuring networks with 20-25 measuring points in each harbour area. The results of this examinations show that in the areas intensively polluted by inland vessels, the air quality with regard to NO_2 pollution was significantly better than expected. In the residential areas adjacent to the port areas, the EU-wide limit value of 40 µg/m³ for annual mean concentrations of NO_2, was safely complied with in all cases. Very detailed data on the various emission sources for the port areas of Duisburg and Neuss, were available from the LANUV NRW. In addition, the traffic emissions as well as the emissions of the industrial trucks in the port areas were recorded for CLINSH. (See CLINSH report "Harbour Monitoring Part C: Emission inventories for the ports of Duisburg and Neuss/Düsseldorf"). These emission inventories, together with the newly developed methods for the recording of ship emissions, provided a good basis for the modelling of the causes of pollution at the air quality measuring points. Model calculations for the analysis of the causes of pollution showed that the main effect of ship emissions is essentially observed locally in the immediate vicinity of the waterways. In residential areas, the effects of road traffic emissions are generally much more pronounced.

Further modelling was carried out within the framework of CLINSH. Air quality modelling is necessary to demonstrate how emission reduction affects the air quality improvement. Only air quality models have the capability to give a comprehensive picture in time and space of the concentrations of air pollutants. To estimate this impact on different scales both urban and regional models are necessary. The concentrations of NO2, NOx and PM10 are calculated for several different scenario's. CLINSH developed a reference fleet inventory for 2020 (s2020b) and two IWT fleet development scenarios towards 2035: one **Baseline scenario** (s2035b) based on "autonomous" engine renewal and one scenario with accelerated emission reduction, referred to as **the CLINSH scenario** (s2035c). The in chapter 3 presented modeling systems (EPISODE CityChem) is intended as a tool that can be applied to any region in Europe using the same publicly available input data for meteorology, boundary

conditions and emissions. This allows for a direct comparison between different areas based on the same assumptions and datasets. Therefore, the presented approach is considered to be a consistent approach. To demonstrate the absolute and relative reduction potentials of the CLINSH inland shipping emission scenarios, runs were performed with the introduced modeling chain. While boundary conditions, meteorology, land-based and sea-going ship emissions were held constant at 2019 conditions, the inland shipping emissions of the different scenarios' were exchanged. While in the base (business as usual) scenario mean reductions of ca. 20-25% for the urban domains are simulated, the Clinsh (accelerated emission reduction) scenario shows a reduction potential of 70-76% for NO2 inland shipping emission impacts in 2035. For PM10 the reduction potentials for the base scenario are 23-27% for Rotterdam, Antwerp and the Western Rhine-Ruhr area, while they are up to 33% for Nijmegen. For the Clinsh scenario the reduction potentials for Antwerp and Rotterdam are 61% and 66%, while for the Western Rhine-Ruhr area the reduction potential is up to 85% and for Nijmegen it is almost 90%. In general, there is a high reduction potential for NO2 in all urban domains, when simulating the clinsh scenario as developed within the CLINSH project. Every country, region and institute uses its own models.

In the Netherlands model is used that consists of a Gaussian plume model, this is very different to the CityChem model. This model is prescribed by the Dutch government to calculate the effect of shipping emissions on the air quality. It was tested if the method developed in Clinsh could be used by other local modals as well, and if the same results were found. The different scenario's were inserted into the OPS model and similar results were found to the CityChem modelCalculations for Rotterdam show that in the Baseline scenario in 2020, inland shipping contributes between 0.2 to 3 µg/m³ with an average of 1,2 µg/m³ to NOx concentrations. In the Baseline scenario in 2035, the contribution from IWT in the Rotterdam region varies between 0.2 and 2.6 µg/m³ with an average of 1.0 µg/m³. The contribution of the shipping is only slightly lower than in 2020. The CLINSH scenario has a significant effect on air quality however: the contribution from IWT to the NOx concentrations in Rotterdam varies between 0.1 and 1.3 µg/m³ with an average of 0.4 µg/m³. Similar results have been calculated for Nijmegen.

The modelling system developed in Clinsh can be used to show the effects of air quality measures (policies) in a consistent way and that can be applied to any region in Europe using the same publicly available input data for meteorology, boundary conditions and emissions, you can also use the scenario's in your own air quality models. However this modeling chain is not suitable for all applications. While it is possible to achieve comparable qualitative results, such as the contribution of a specific emission sector in different cities or regions, the presented modeling chain and results in this report are not sufficient for air quality reporting. To suffice for air quality reporting the air quality simulations performed within the CLINSH project would need in-depth analysis and city-specific inventories and parametrization, which is generally possible but out of the scope of this project.

Through the air quality calculations we have shown that the Clinsh scenario can significantly reduce air pollution in urban areas. Especially in cities like Rotterdam where there is housing close to the harbor and the river the air quality in these areas can be considerably improved. For over 150,000 inhabitants, the NO_x concentration decreases by 0.13 to 0.5 µg/m³. For over 27,000 inhabitant the NO_x concentration decreases by 1.25 to 1,50 µg/m³. Concentration levels of the modelled pollutants are an important indicator for health risks and represent important data for the socio-economic assessment in action C1. They are additionally needed to determine the impact the impact of abatement technologies in the future. This action is an important link between the demonstrations and possible future policy.

Contents

1 Introduction

The main objective of CLINSH is to improve air quality in urban areas by accelerating emission reductions in Inland Waterway Transport. Important sub-goals within the CLINSH project are:

- To demonstrate the effectiveness of greening measures in the IWT sector
- To stimulate the sector to personally take these greening measures
- To contribute to improving air quality.

The key objective of Action B4 is a sub-objective of the Clinsh project: *Demonstrate the effect of different scenario's on air quality by using high resolution modelling.* To estimate the impact of inland shipping on air quality measuring of air pollutants concentrations and modelling is required. To guarantee a sound comparison between regions different transnational approaches for modelling

Air quality modelling is necessary to demonstrate how emission reduction affects the air quality improvement. Due to non linear effects in transport and chemistry of air pollutants, conclusions about the impact of emission changes alone on air quality can't be drawn. Only air quality models have the capability to give a comprehensive picture in time and space of the concentrations of air pollutants. To estimate this impact on different scales both urban and regional models are necessary. The concentrations of NO2, NOx and PM10 are calculated for several different scenarios. CLINSH developed a reference fleet inventory for 2020 (s2020b) and two IWT fleet development scenarios towards 2035: one **Baseline scenario** (s2035b) based on "autonomous" engine renewal and one scenario with accelerated emission reduction, referred to as **the CLINSH scenario** (s2035c). Both scenarios are built on the same assumptions regarding market developments of transport volumes (e.g. coal, oil products) and related developments in vessel and fleet size and include a modest uptake of Zero Emission technologies. Concentration levels of the modelled pollutants are an important indicator for health risks and represent important data for the socio-economic assessment in action C1. They are additionally needed to determine the impact the impact of abatement technologies in the future. This action is an important link between the demonstrations and possible future policy.

Four regions are defined as show cases to demonstrate the impact of inland emissions on the air quality: the ports of Rotterdam and Antwerp, a region around Nijmegen and a region around Düsseldorf and Duisburg.

The steps to estimate the impact of inland shipping on air quality for a baseline year and for future years are Parameterisation of dispersion characteristics for air quality modelling

1) Validating and evaluating air quality modelling results
2) Model runs
3) Mapping model result

2 Air quality measurements and methods for the estimation of shipping emissions

The *EU Air Quality Directive*[1] provides limit values for air pollution with nitrogen oxides and particulate matter for inhabited or publicly accessible areas. The EU member states are obliged to comply with these limit values and to monitor air pollution. The most reliable method for carrying out these checks is to measure air pollution using standardized measurement methods. The EU prescribes a minimum number of measuring points per unit area. Ideally, all expected "hotspots" should be monitored with measurements.

These measurement methods are very costly and can therefore not be used across the board. Alternatively, modelling methods can also be used to monitor air quality, but depending on the modelling method used, they usually provide significantly less reliable results.

Due to the high variability of the informative value of the different models and the uncertainties in the input parameters (such as emissions, meteorological data and dispersion characteristics), the model results must be validated with real data. This is done using observational data from Clinsh measurement campaigns and the results of national and regional air quality networks. When modelling for the EU Air Quality Directive, it is partly common practice to calibrate the modelling results on the real measured values.

In the combination of real measured values and extensive data on the location of the emission sources and the emission quantities of the individual pollution sources (e.g. industry, domestic heating, road traffic, etc.), it is also possible on the basis of the measured values to analyze the respective shares of the individual sources in the air pollution present at ground level.

In the large cities along the Rhine, the amount of emissions from inland navigation can easily reach the magnitude of emissions from road traffic. In the discussion about the causes of exceeding the EU limit values for nitrogen dioxide in many cities over longer periods of time, also ship emissions came into focus of the debate in NRW.

Due to EU regulations, there have so far only been a few measuring stations in the official monitoring networks that were suitable for a detailed analysis of the effects of emissions from inland waterway vessels and port operations on air pollution. Within the framework of CLINSH, the LANUV NRW has taken the opportunity to carry out intensive measurement programmes on the Rhine and in the ports of Duisburg (Europe's largest inland port) and the second largest inland port in North Rhine-Westphalia in Neuss/Düsseldorf.

Chapter 2 presents a summary of the results, the detailed results can be found in the full report *"Harbour Monitoring Part A: Air quality on the Rhine and in the inland ports of Duisburg and*

[1] **DIRECTIVE 2008/50/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 May 2008 on ambient air quality and cleaner air for Europe**

Neuss/Düsseldorf. Immission-side effect of emissions from shipping and port operations on nitrogen oxide pollution" .

The program ran from December 2017 to May 2019. A very high measurement site density was selected for the measurement programs in order to be able to carry out detailed cause analyses using LASAT modelling. For the CLINSH measurement campaign from 2018, the modelling of the LANUV for the clarification of the pollution shares of the detected air pollution (cause analysis) showed a good agreement with the real measured values. For the CLINSH measurement campaign from 2018, the modelling of the LANUV for the clarification of the pollution shares of the detected air pollution (cause analysis) showed a good agreement with the real measured values. For the CLINSH measurement campaign from 2018, the modelling of the LANUV for the clarification of the pollution shares of the detected air pollution (cause analysis) showed a good agreement with the real measured values.

The results of these root cause analyses are compiled in the CLINSH report: "*Harbour Monitoring Part F: Root Cause Analyses for Air Quality Measurement Results in the Inland Ports of Neuss and Duisburg)*"

Additional measurement programs were set up at the German-Dutch border and also at the border to Rhineland-Palatinate directly on the banks of the Rhine in order to be able to directly assess the effects of emissions from passing ships to air quality on the basis of load increases.

With the automatic measuring stations, the pollution of the air with nitrogen oxides was measured every 5 seconds. With suitable wind directions, the emission peaks of the passing ships became visible, which can be quantified via the peak area. At the same time, the identification of the passing ships was made possible by recording the AIS signals.

Due to an evaluation of approx. 16,000 onshore measurements recorded in this way, it was possible to develop onshore emission factors for NO_X, classified according to ship size, direction of travel (upstream, downstream) and speed over ground.

With this database developed in the CLINSH project, it became possible to realistically determine the actual emissions of passing ships using onshore emission factors based on real measurement data with a newly developed modelling method. The LANUV NRW has already successfully applied this method for the NO_X emission calculations for the study areas Neuss/Düsseldorf and Duisburg. The method is to be used also for the planned update of the emission register "inland waterway vessels" in NRW. Details on the method development and application of the onshore emission factors were compiled in the CLINSH report: *"Harbour monitoring Part E: Determination of NOX emission rates of passing vessels from onshore measurements, comparison to onboard observations and application for emission calculations".*

A practicable method for the realistic calculation of emissions from ships at berth was not available from any CLINSH partner. Since realistic data was needed for the modelling within the framework of the port monitoring in order to be able to include these emissions as point or line sources in the cause analyses, the LANUV developed a new methodology within the framework of CLINSH.

Details on the development of the methodology and the application of the onshore emission factors were published in the CLINSH report: *"Harbour Monitoring Part B: Determination of NO_X and particulate matter emissions from inland vessels at berth"*.

2.1 Monitoring in the port areas of Duisburg and Neuss/Dusseldorf

The focus of the investigations was on air quality pollution from ships and port operations in the ports of Neuss and Duisburg. In both study areas, very extensive measurement networks were set up by the LANUV for the "CLINSH Special Measurement Programme" to record air pollution with nitrogen dioxide (NO_2). The location of the measuring points was chosen in such a way that, in addition to the emissions caused by shipping, other sources in the port area such as port railways and lorry traffic could also be assessed and modelled within the framework of polluter analyses.

A total of 53 measuring stations with passive collectors for NO_2 and two automatic measuring stations were included in the investigations. The investigations ran from December 2017 to May 2019. The automatic measuring station in Neuss (NERH) was operated until December 2019, the Duisburg measuring station has continuously been running since December 2017.

The measurement results of the CLINSH project in the ports of Neuss and Duisburg show that despite the spatial proximity of the sources "port" and "inland vessel", the contribution to urban air pollution from shipping traffic cannot be of the order of magnitude assumed at the time. All measuring points of the special measuring programme, which were located in or close to residential areas in Duisburg showed annual mean values for NO_2 concentrations in a range of 33 and 36 µg/m³ for 2018. The annual mean values at the monitoring sites located directly on the Rhine near Duisburg also ranged from 26 µg/m³ to 30 µg/m³ for the windward (left) bank and from 27 µg/m³ to 32 µg/m³ for the leeward (right) bank. All NO_2 annual mean values positioned in the immediate vicinity of the emission source "shipping traffic on the Rhine" were thus clearly below the EU limit value of 40 µg/m³ (Fig.1 &2).

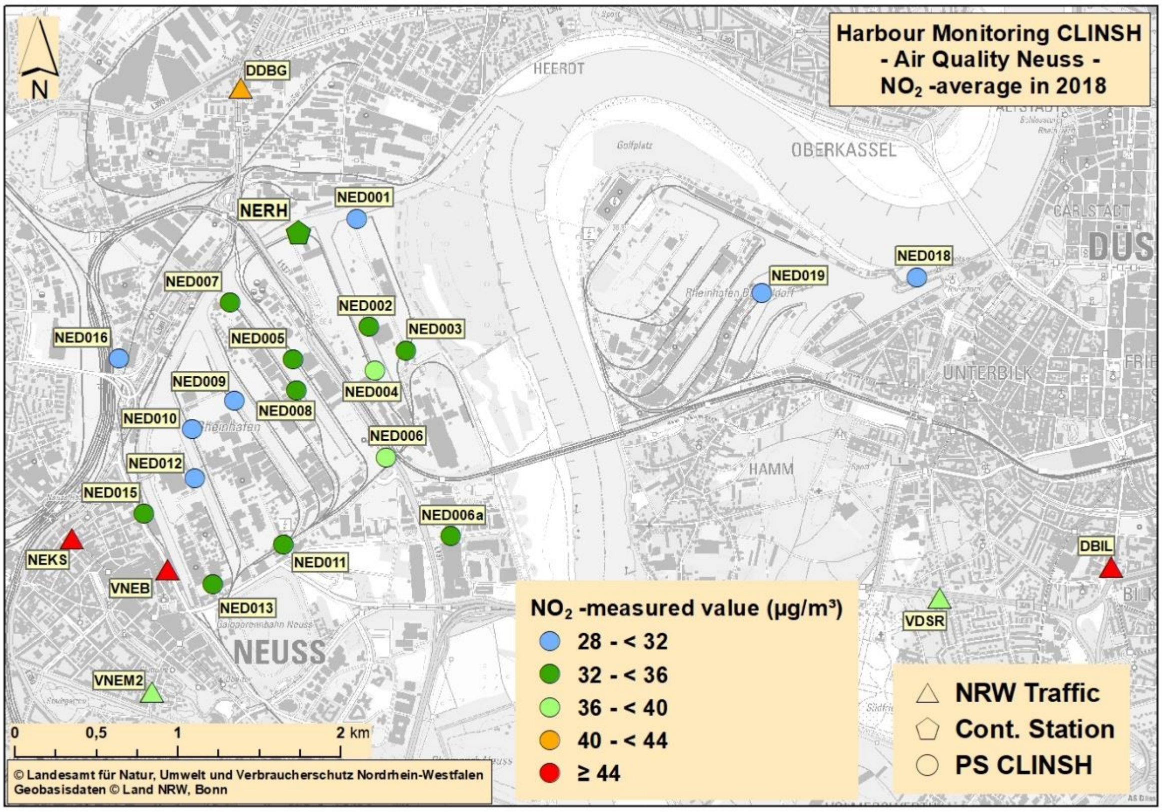

Figure 1: NO_2 concentrations in Neuss harbour - Classified annual mean values 2018

At the measuring points located directly on the Rhine in the Duisburg area, annual mean values of 26 µg/m³ to 30 µg/m³ were measured on the windward side of the left bank and 27 µg/m³ to 32 µg/m³ on the leeward side of the right bank. Compared to the background pollution, site-specific increases in

NO_2 pollution in the range of 6 µg/m³ to 11 µg/m³ were recorded for the measuring sites located directly on the Rhine in Duisburg in 2018. The air quality of these locations is influenced by local sources such as inland shipping, road traffic, domestic heating, etc. as well as industrial emission sources.

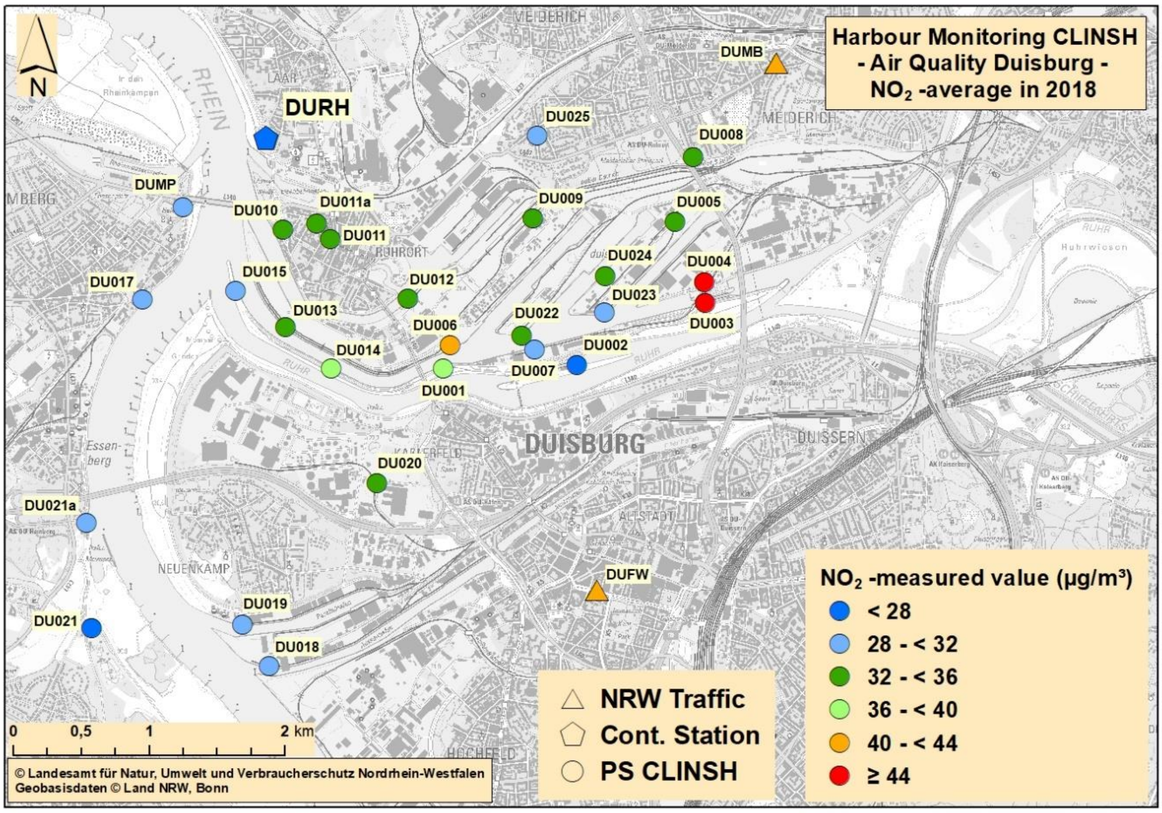

Figure 2: Air pollution with NO_2 in Duisburg harbour - Classified annual mean values 2018

2.1.1 Results of the automatic measuring stations at Duisburg and Neuss/Dusseldorf

After the start of the project, the LANUV had the opportunity to use two continuous measuring stations in addition to the passive collectors for the CLINSH program. At the end of 2017, a continuous measuring station was installed both in the Neuss harbor area and in Duisburg, which enabled high-resolution measurements of nitrogen oxides (NO and NO_2, sum NO_X), the recording of fine dust pollution, the recording of AIS signals and data on meteorology.

The multi-year measurement results of the automatic measuring stations show a decrease in pollutant concentrations in the years 2018-2020 (Tab.1). At both measuring stations (DURH; NERH), a similar decreasing concentration development was observed over the years for the annual parameters for NO_2 as well as for PM_{10}, as already described for the NO_2 concentrations at the German-Dutch border. At both monitoring stations, which are directly influenced by shipping and port operations, the annual mean values are well below the limit values of the *EU Air Quality Directive*[2].

[2] **DIRECTIVE 2008/50/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 May 2008 on ambient air quality and cleaner air for Europe**

Station	Year	NO_2 (µg/m³) Annual average	PM_{10} (µg/m³) Annual average	PM_{10} Daily mean with exceedances of 50 µg/m³
DURH	**2018**	**27**	**23**	**10**
	2019	**26**	**19**	**2**
	2020	**21**	**22**	**1**
NERH	**2018**	**33**	**22**	**6**
	2019	**30**	**19**	**3**

Tab. 1: Annual parameters for NO_2 and PM_{10} at the two continuous monitoring stations in Neuss (NERH) and Duisburg (DURH)

With the data from the automatic measuring stations, it is possible to derive further statements on the effect of ship emissions. Figure 3 shows the analysis of the distribution of the occurring wind directions in 2018. South-westerly and north-easterly winds mainly occurred.

Figures 4 and 5 show the mean NO_X and PM_{10} concentrations occurring in the respective wind directions. When the wind blows in westerly directions across the Rhine and carries the ship emissions to the station, the average NO_X and PM_{10} concentrations are lower than in the onshore wind directions. This is a first indication that the contribution of ship emissions to air pollution is lower than assumed at the start of the project.

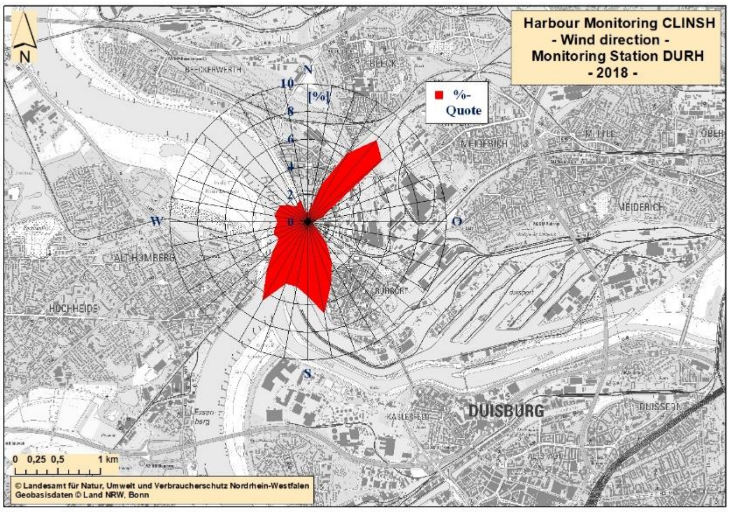

Figure 3: Percentage distribution of wind directions occurring in 2018 at the DURH station in Duisburg

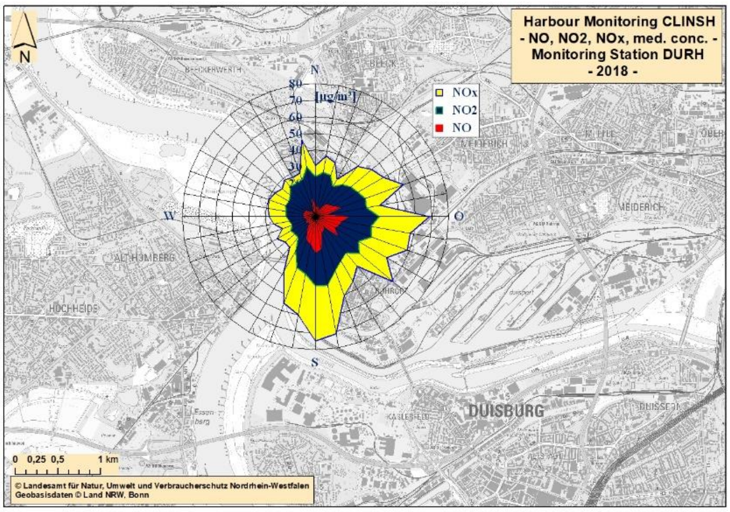

Figure 4: Measured mean NO, NO_2 and NO_X concentrations with different wind directions at the DURH station in Duisburg

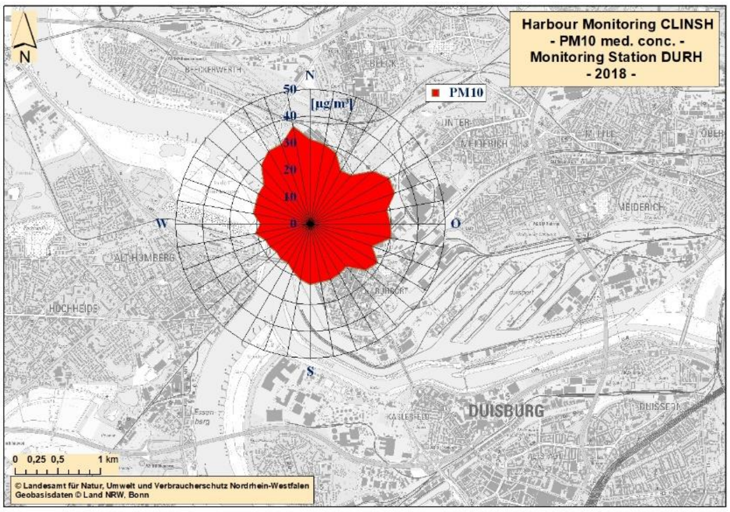

Figure 5: Measured mean PM10 concentrations at different wind directions at the DURH station in Duisburg

2.1.2 Modelling of the causes of air pollution in Neuss and Duisburg in 2018

For the CLINSH air quality monitoring programmes in the ports of Duisburg and Neuss, the LANUV carried out extensive modelling to analyze the causes of the air pollution. The aim was to determine more precisely the contributions of ship emissions and port operations to the measured pollution. The emission register of the state of North Rhine-Westphalia maintained by the LANUV and the results of special surveys for the CLINSH project for the entire study area were used as input data. The cause modelling for the actual harbour areas was carried out with LASAT. In the narrower harbour areas (frame in the figures) a very narrow grid (nested grid) of 5*5 m was applied. The railing structures were also taken into account.

Since there are many large halls in the harbour areas, which can have a significant influence on wind directions and air turbulence, the building geometries were also included in the modelling. The modelling procedure used for CLINSH is thus exceptionally complex and requires enormous computing times. Fig. 6 shows the modelled greater area as well as the narrower harbour areas.

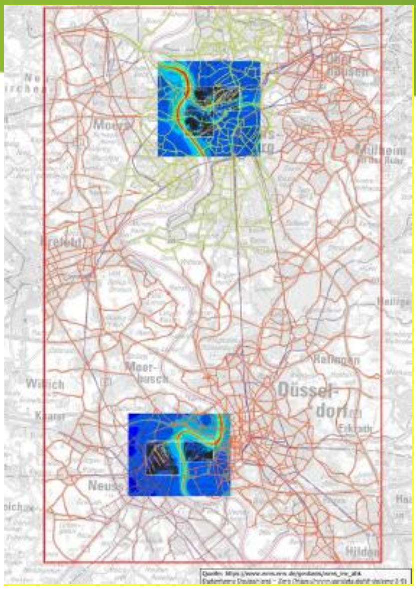

Figure 6: Modelling areas for CLINSH port monitoring.

Internal combustion engines and other emission sources usually emit a mixture of different nitrogen oxides. The compounds nitrogen monoxide (NO) and nitrogen dioxide (NO_2) are the main components. However, they do not remain constant in the proportion in which they are emitted. Through various mechanisms of air chemistry, these compounds can change rapidly. Concentration ratios and other air chemicals such as ozone play an important role here.

Diesel engines, for example, emit predominantly nitrogen monoxide, which, however, in some cases converts very quickly to NO_2 in the air. For the modelling of causes of pollution, therefore, the sum of both parameters (NOX) is always considered, with the NO being converted into NO_2. This procedure was also used for the cause analysis of the two CLINSH measurement programmes in Duisburg and Neuss.

Modelling of air pollution is often carried out without reference to the real (measured) air pollution. Depending on the model and the input parameters used, results can be generated that do not correspond to the real air pollution levels, but instead can sometimes significantly overestimate or underestimate them. Therefore, for the purposes of determining the causes of air pollution control and measures to reduce air pollution, it is essential to establish a reference to real measured values. Hence, modelling results always require validation (quality assurance) based on real measurement results. Only in this way the actual effect of mitigation measures can be estimated in a practical manner.

For the measurement programmes carried out in Duisburg and Neuss, within the framework of CLINSH, the modelling showed good agreement with the real pollution levels of the CLINSH measurement points in the port areas and the traffic measurement points of the official measurement networks. The modelling refers to the average load over the year 2016. In the following, the modelling results are presented using the example of the Neuss/Düsseldorf port area.

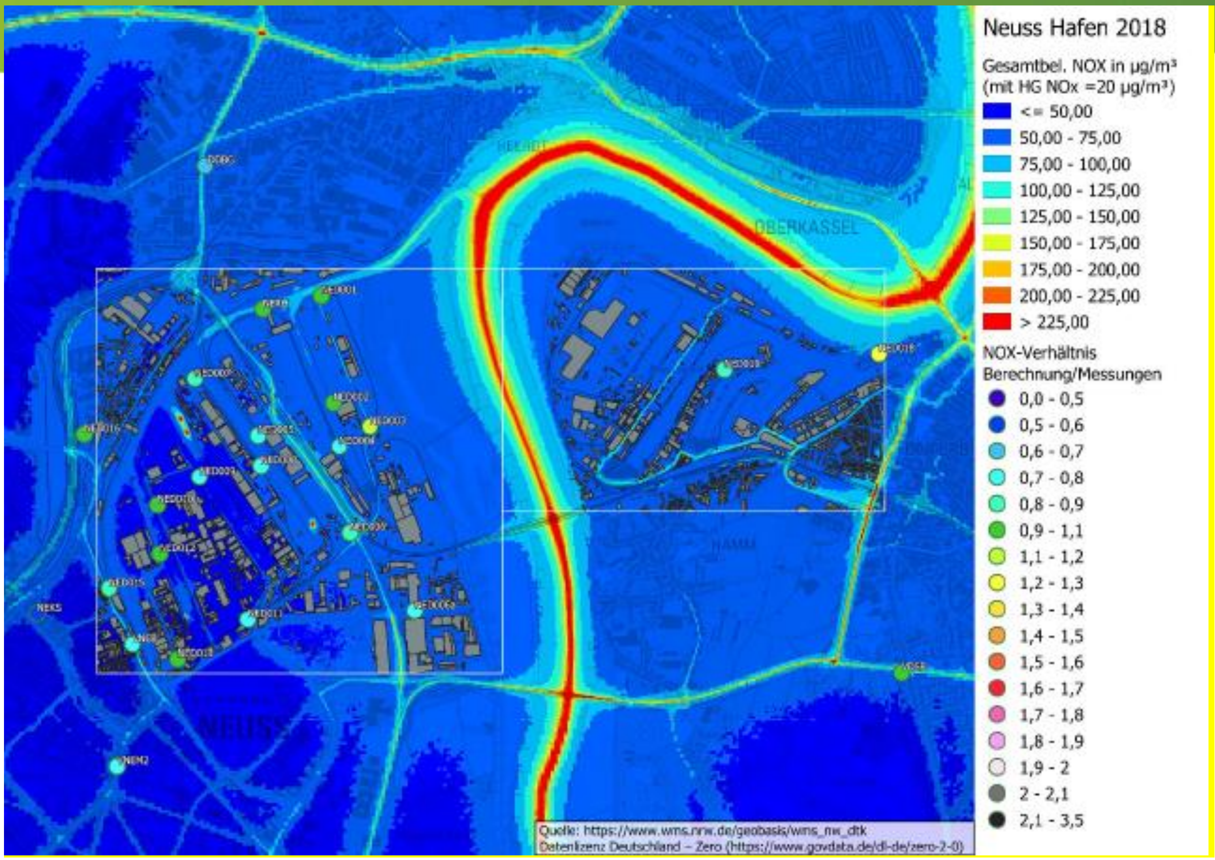

Figure 7: Two-dimensional representation of the total NO_X load in the Neuss/Düsseldorf port area. Circular representations : Degree of agreement between the modelled load and the actual measured load. EU quality criterion for modelling for the EU Air Quality Directive : real value +/- 30 %.

Figure 7 shows the high emission density of inland vessels on the Rhine, which clearly shows the character of a line source. The emission density caused by about 200 ships per day is comparable to the conditions of a busy four-lane motorway.

Fig. 8 shows the proportion of ship emissions on the Rhine in the total pollution as a two-dimensional representation. In the Neuss harbour area (west of the Rhine), the shares of total pollution are in the range of 10-20 %. In the area of Düsseldorf-Oberkassel, ship emissions also account for 30-40 % of the pollution in residential areas. This is mainly due to the bend in the Rhine near Heerdt, which causes ship emissions to reach the neighbouring residential areas about twice as much.

Fig. 9 shows the share of emissions from shipping and port operations in the port of Neuss. It is clear that these emissions have only a fairly minor impact on air quality in the surrounding area. The berths of the tankers are clearly visible as small-scale red pollution hotspots.

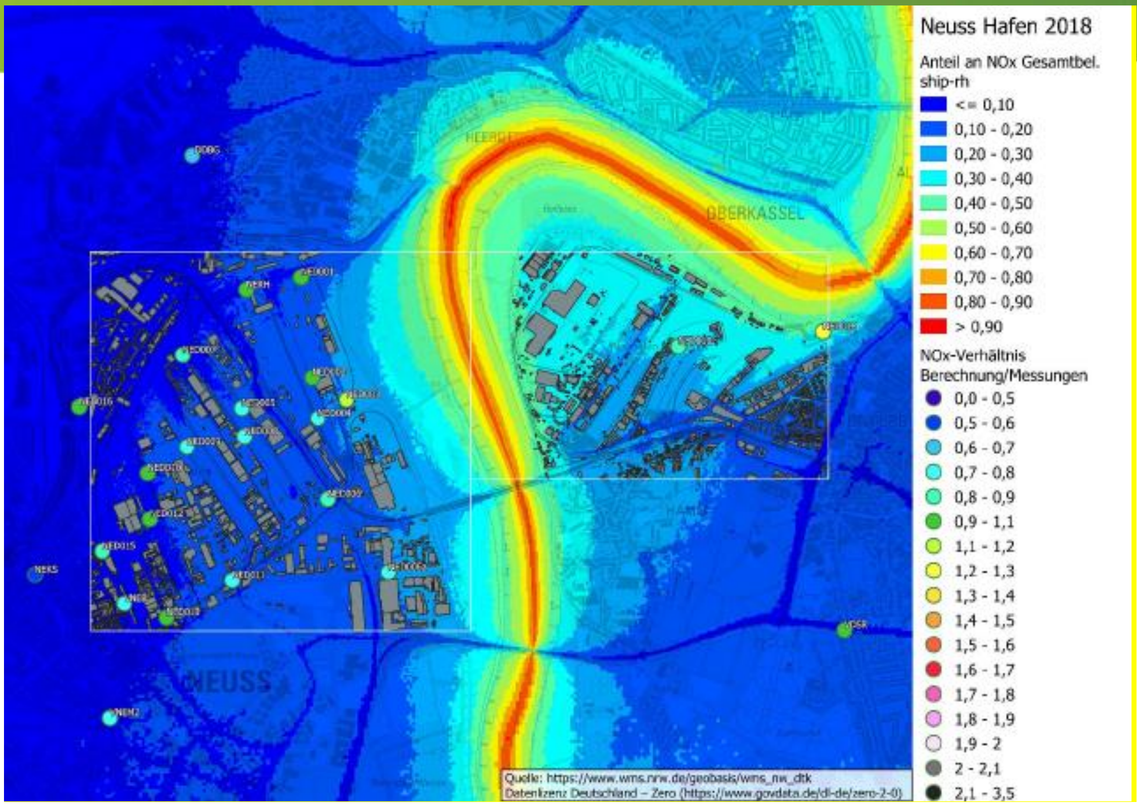

Figure 8: Two-dimensional representation of the shares of ship emissions on the Rhine of the total load

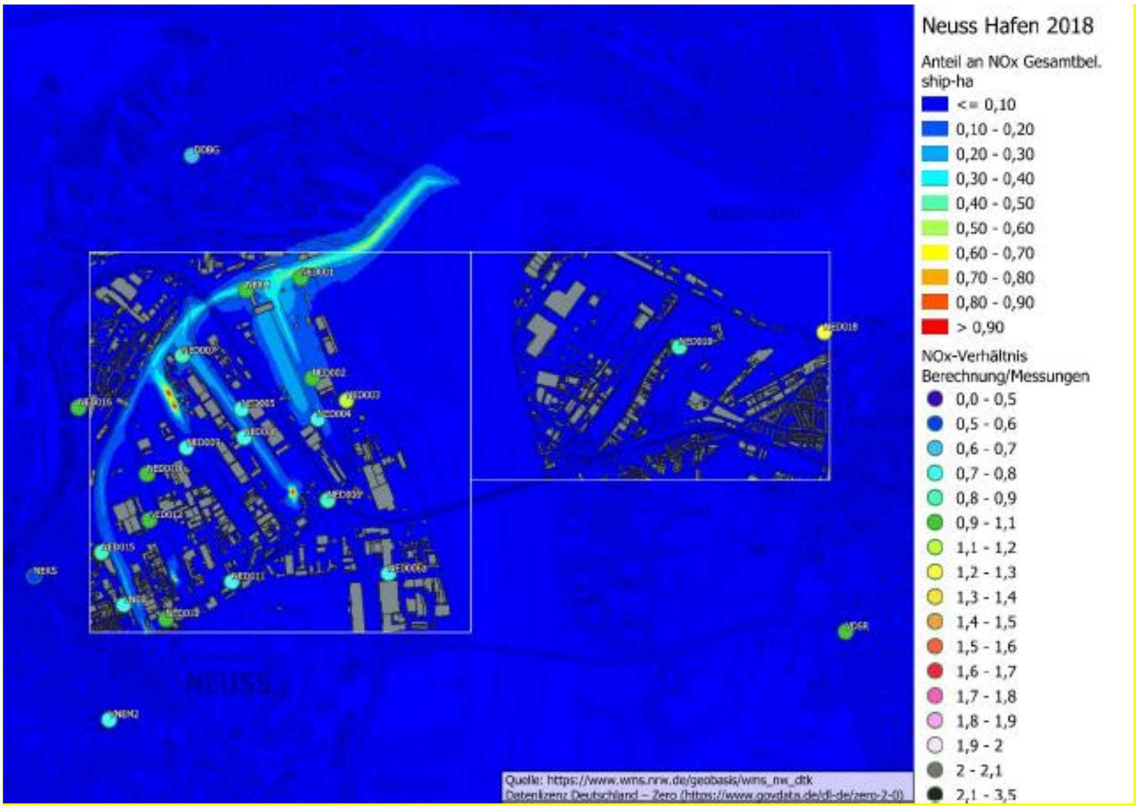

Figure 9: Two-dimensional representation of the port operation's share of the total load

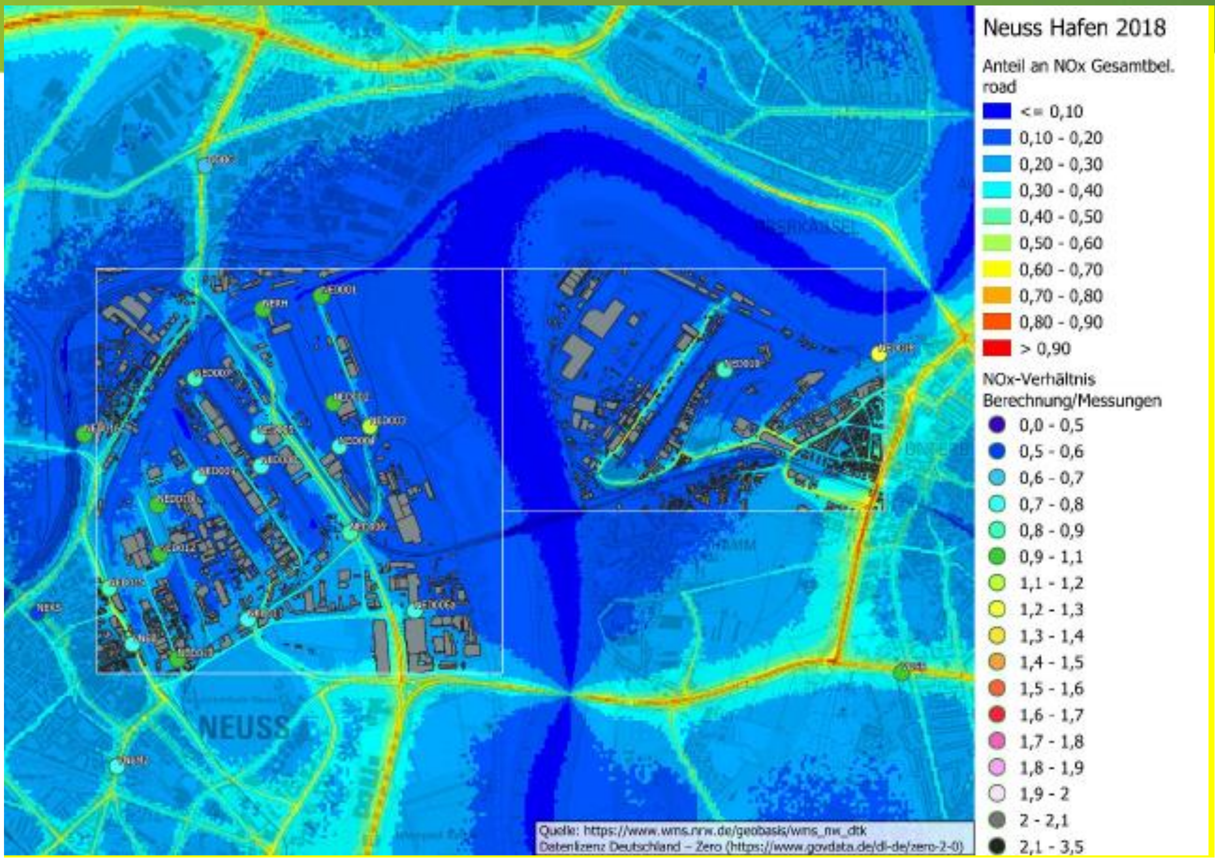

Figure. 10: Two-dimensional representation of the share of road traffic of the total load

Figure 10 shows the areal effect of emissions from motor traffic. Here it becomes clear that the busy main roads have a detrimental effect on the air quality in their vicinity. In most cases, road traffic is the main cause of non-compliance with the EU limit value for NO_2.

2.1.3 Measurable influence of inland vessels on air quality

The aim of the study was to record the NO_2 pollution of the air directly on the banks of the Rhine by means of passive samplers. The place with the highest traffic density of inland vessels in NRW is the German-Dutch border in the area of Bimmen/Lobith. More than 100,000 ship movements per year are registered. The border of NRW to Rhineland-Palatinate was also investigated because here the influence of ship traffic to and from NRW is the section with the lowest traffic density of inland vessels on the Rhine in NRW.

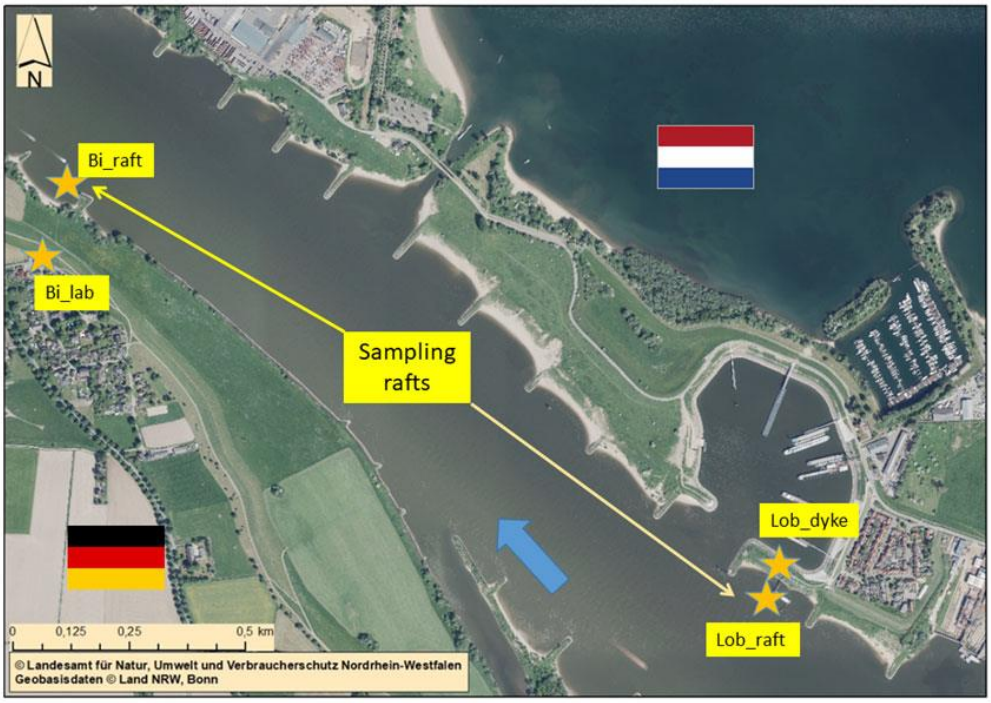

Figure 11: Measurement sites on the German-Dutch border

The CLINSH measurement programme in Bimmen-Lobith ran from April 2016 to December 2020. The estimation of the rural background pollution was carried out by means of the results on the windward side of the dike crest. The annual mean NO_2 value measured here was 17-18 µg/m³ in 2017 and 2018. In 2019, the value dropped to about 16 µg and in 2020 further to 13.5 µg/m³. This background pollution in the Bimmen area already includes a share of large-scale distributed inland waterway vessel emissions in the Lower Rhine region in the order of approx. 0.5-1 µg/m³. A modelling of the ubiquitous NO_2 pollution in the metropolitan area of Duisburg in 2016 by means of the EURAD model by the *Rheinisches Institut für Umweltforschung (University of Cologne)*[3] resulted in a value of 15.6 µg/m³. This value corresponds well with the values measured in Bimmen in 2017-2019 and shows that no significant local pollution sources are effective in Bimmen with the prevailing westerly wind directions.

At the measuring point on the measuring raft on the left bank, an annual mean NO_2 value of 19.8 and 19.4 g/m³ was obtained (windward side) in 2017 and 2018. Compared to the concentrations at the top of the dike (Bi_lab), the concentration here was about 2 µg/m³ higher in both years. It can be assumed that this increase was caused solely by inland shipping. In 2019 (16.8 µg/m³) and 2020 (14.1 µg/m³), the concentrations on the left, windward sampling raft also decreased. The difference in the increase in concentration caused by shipping (conc. Bi_raft - conc. Bi_lab), which decreases progressively over the years, is striking here. In 2019, the difference was 1.0 µg/m³ and fell further to 0.6 µg/m³ in 2020 (Fig. 12).

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[3] **Modellanalyse Schadstoffimmissionen Auswirkungen des Verkehrs auf die Luftqualität in drei Ballungsräumen; FE 02.0414/2017/IRB; Abschlussbericht vom 30.09.2020 Rheinisches Institut für Umweltforschung an der Universität zu Köln, erstellt für die Bundesanstalt für Straßenwesen (BASt), Bergisch Gladbach, unveröffentlicht**

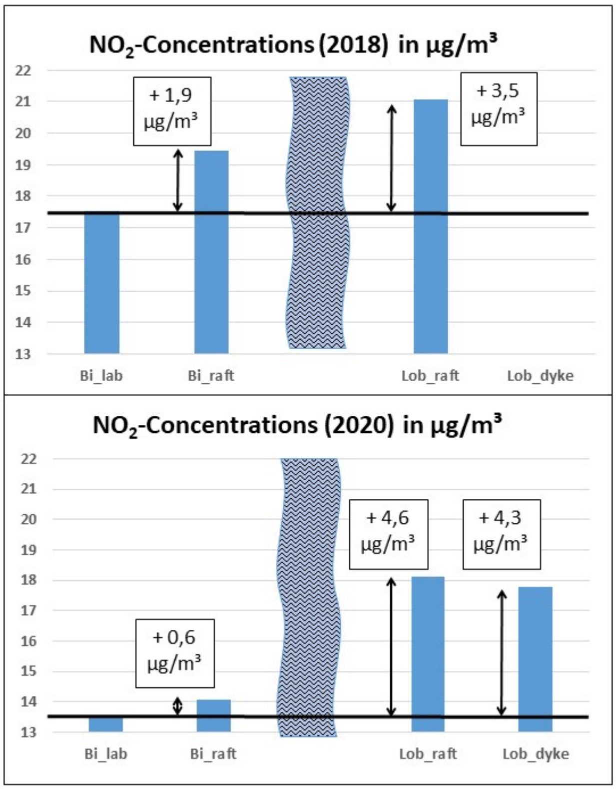

Figure 12: Development of NO2 concentrations at the Rhine near Bimmen/Lobith

Since the wind at the German-Dutch border comes predominantly from westerly directions, it is to be expected that the ship exhaust gases predominantly have an effect on the right, eastern bank of the Rhine. In 2017 and 2018, the annual mean NO_2 value here was 21 µg/m³. In 2019 (20.6 µg/m³) and 2020 (18.1 µg/m³), the annual mean values also decreased on the Lobith sampling raft, but not as significantly as on the left bank.

The concentration increases for NO_2 detected on the right bank raft show a clear increase over the course of the study years compared to the results on the left-hand embankment ("background pollution", Bi_lab). The concentration increases compared to the Bi_lab monitoring site were in the range of +3 µg/m³ to +3.6 µg/m³ in 2017/2018. In 2019, this difference increased to +4.8 µg/m³ and was +4.6 µg/m³ in 2020. Under the assumptions described above, these differences are attributable to the emissions of the passing inland vessels.

The uneven development of the differences could have two causes:
a. Shifting of upstream ship traffic to the right side of the river, possibly caused by low water levels on the left side of the Rhine in combination with decreasing flow velocities on the right side.
b. Stronger share of westerly wind directions in 2019 and 2020. Unfortunately, a more detailed analysis of the causes of these displacement effects was not possible within the CLINSH project.

2.1.4 Conclusions of the results at Bimmen./Lobith

Based on the measurements carried out on the Rhine in Bimmen/Lobith, the impact of ship emissions (approx. 110,000 ship passages per year) can be estimated quite well.

In all three years of investigation, higher concentrations have been found on both rafts of the IMBL, located directly on the Rhine, than on the windward dike. The only locally effective emission source here is the inland waterway traffic on the Rhine. On the windward, left bank of the Rhine, increases in the NO_2 concentrations (annual mean), detectable in the air, in the range of 1- 2µg/m³ were traceable. On the leeward bank, concentration increases in the order of 3 to 5 µg/m³ could be detected-It can be assumed that the concentration increases (annual mean), detectable on the two measuring rafts on the left and right bank of the Rhine, are the direct effects of the approximately 110,000 annual inland waterway vessel passages.

The Rhine section with the most ship passages for NRW is located at the German-Dutch border in the Bimmen-Lobith area (Rhine km 865). Upstream, the number of passing ships steadily decreases. Compared to Bimmen, the number of ships below the port of Duisburg (km 782) is still about 70%, below Neuss (km 744) about 57% and shortly before the border to Rhineland-Palatinate (Bad Honnef, km 640) about 45%. It is therefore to be expected that upstream, due to the decreasing number of moving ships, the ship-related shares of air pollution in the cities along the Rhine will decrease.

2.2 Emissions of shops at berth

For the modelling of the cause analyses within the framework of the CLINSH port monitoring, realistic data about NO_X and PM emissions were required in order to be able to include these emissions as point or line sources in the cause analyses. Since a practicable method for the realistic calculation of emissions from ships at berth was not available from any CLINSH partner, the LANUV also developed a new methodology within the framework of CLINSH.

The fundamental data was:

- Determination of the energy demand of moored ships
- Detailed evaluation of the current generator fleet on inland vessels
- Development of suitable average emission factors per ship type and ship size
- Recording of ship numbers at the berths
- Recording of average berthing times.

Details on the method development and application of the onshore emission factors were published in the CLINSH report: *"Harbour Monitoring Part B: Determination of NOX and particulate matter emissions from inland vessels at berth"*. The LANUV NRW has already successfully applied the new method for the NO_X and PM_{10} emission calculations for the study areas Neuss/Düsseldorf and Duisburg. The emissions of the moored cargo ships can be represented as line sources. Tankers are bound to fixed loading points, so that these emissions can be represented as point sources (Fig. 13).

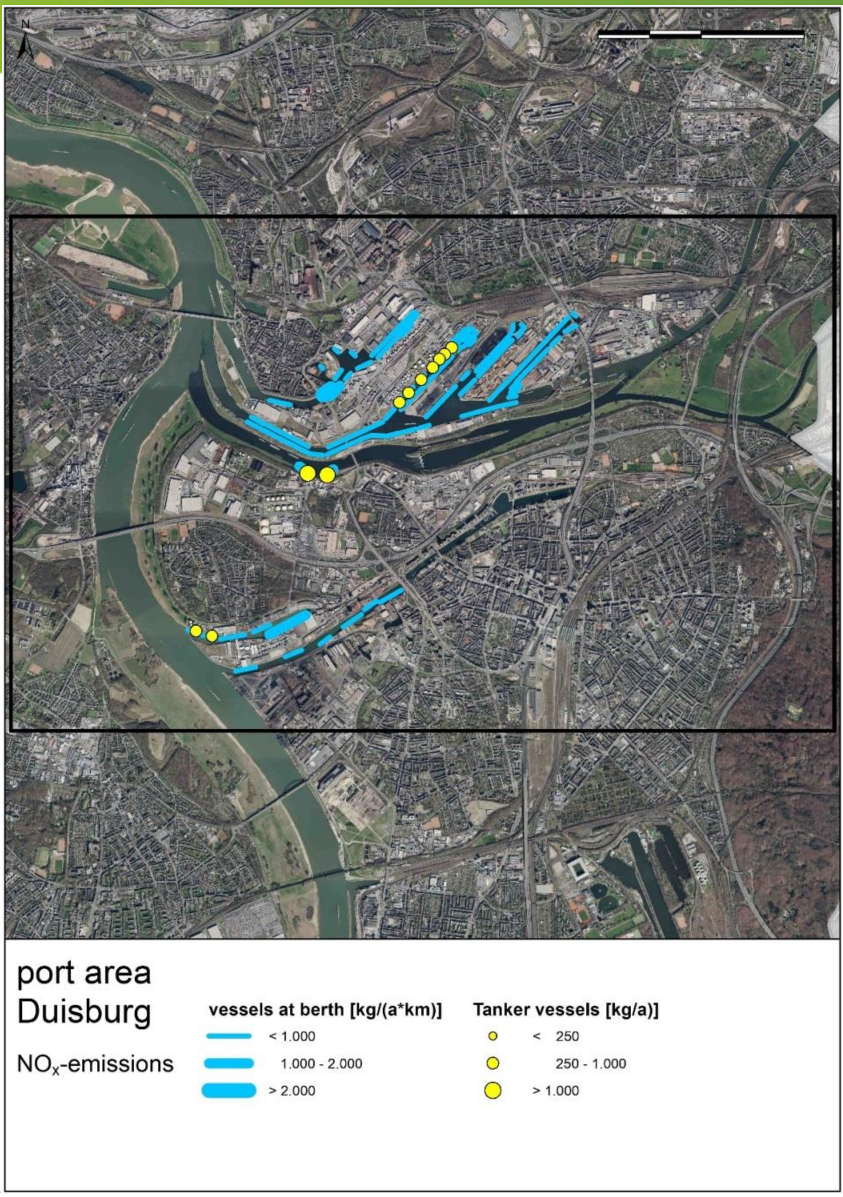

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Figure 13: Emissions from berthed ships as point and line sources using the example of the Duisburg port area.

2.3 Recording of the emission peaks of the moving shops by the automatic measuring stations

With the automatic measuring stations, the pollution of the air with nitrogen oxides was measured every 5 seconds. With suitable wind directions, the emission peaks of the passing ships became visible, which can be quantified via the peak area. At the same time, the detection of the AIS signals made it possible to identify the passing ships (Fig. 14).

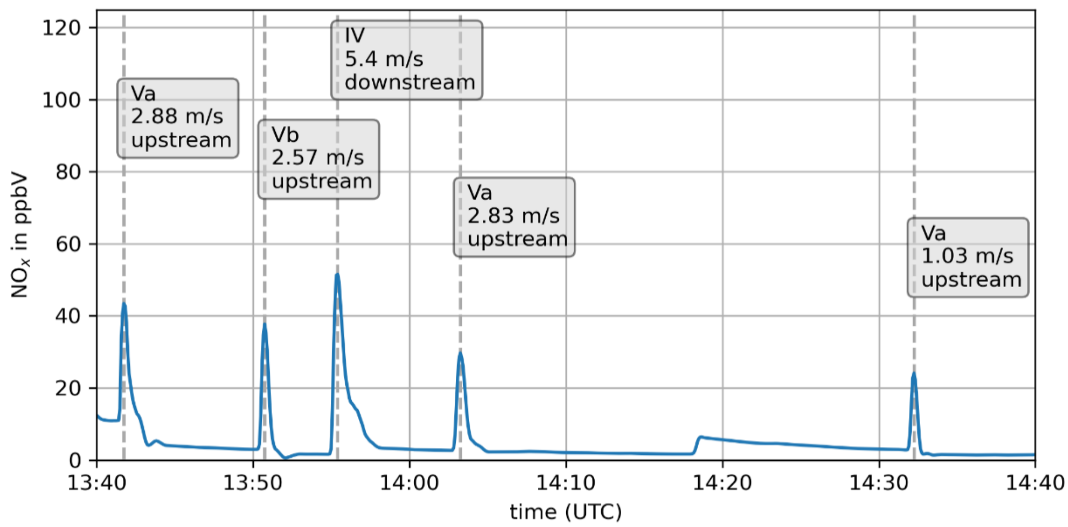


Figure 14: Assignment of NOx peaks to the direction of travel, speed and length classes of the passing vessels by means of AIS signals

IV : Europe vessel (Rhine-Herne Canal vessel): 85 × 9.50 × 2.5 m, cargo capacity 1,350 t
Va : Large Rhine vessel: 110 × 11.4 × 3.5 m, cargo capacity 2,800 t
Vb : Large Rhine vessel: 135 × 11,4 × 3,5 m. cargo capacity 4,000 t

In cooperation with the University of Bremen, it was possible to determine the corresponding NO_x emission factor in addition to ship size, direction of travel and speed on the basis of the continuous measurement of the DURH station for more than 16,000 ship passages.

With these evaluations, it was possible to derive emission factors for the passing ships from the onshore measurements and to classify them with regard to direction of travel, speed and ship size. These classified data form an important basis for developing a new method for more realistic recording of the emissions actually caused by moving inland vessels on the basis of real emission measurements and the associated speeds (over ground).

With the automatic measuring stations, the NO_X emission peaks (measuring frequency 5 sec) of passing ships can be identified and quantified. The assignment to the ships is done by recording the AIS data. With more than 16,000 quantifications from real measurement results, it was possible to compile a catalogue of onshore emission factors for inland vessels on the Lower Rhine, classified according to vessel size, direction of travel (upstream/downstream) and speed over ground.

With this catalogue and the recording of real ship traffic, a new method for determining the emissions of moving ships was developed and applied for the study area Neuss-Duisburg within the framework of CLINSH. The emission data are now no longer based on estimates of theoretical diesel consumption from performance/emission curves but on real measured onshore data.

Due to traffic density, river morphology, flow conditions, current quays as well as harbour and canal entrances, the speed of the moving ships is not homogeneous and changes frequently. Since different pollutant quantities are also emitted at different speeds, the calculation of emissions and the determination of emission density for modelling should be carried out in sections, e.g. per river kilometer. For the speed classification, speed classes were defined in steps of 1.0 m/s, which was also used as a basis for determining the emission factors. With this classification, an emission calculation can be made for any combination of direction of travel, ship speed and ship size.

With the acquisition and evaluation of AIS data, it is possible by using a suitable evaluation programme, to record the real ship traffic with regard to ship type, ship size, direction of travel and speed over ground. Vessel traffic on the Rhine is not uniform. Differences in ship numbers and ship sizes can occur, mostly due to different water conditions of the Rhine.

The range of AIS transmitters and receivers is limited. The range of AIS transmitters depends on the transmitter strength and the antenna height. Large container ships with the bridge raised have a much greater range than ships with a lower antenna height. On the Lower Rhine, AIS signals can be reliably received within a radius of about 10 river kilometers. With greater distance, the number of ships detected by the station decreases continuously until only individual, mostly larger container ships are detected.

Data gaps between the "safe" reception sections can be closed by interpolating the data, taking into account special local situations (e.g. large port in the unsafe area). Due to equipment failure and transmission disturbances, data gaps can occur temporarily, covering several hours, several days or even longer periods. These gaps must be filled by a suitable method if the annual number of ships is to be determined.

This development of a new method for the calculation of ship's emissions is an important result of the CLINSH measurement programmes. Thus far, as in the old cadastres, the average speeds of the ships had to be estimated and, based on this estimate, the emission events had to be derived from mean power curves of theoretical engines. Such methods have many different, high error rates. With the new method, a more realistic estimation of the emissions of moving ships is possible. The method developed within the framework of CLINSH will also be one of the new bases for updating the emission register *(NRW Shipping emission cadastre for inland vessels*)[4] maintained for North Rhine-Westphalia.

For the LANUV modelling, the emissions of the moving ships were calculated realistically with the newly developed method using the new factors and the evaluation of the AIS data. These data are included in the LANUV modelling in georeferenced form as line sources (Fig. 15).

[4] **Emissionskataster für den Schiffsverkehr in NRW 2012, LANUV-Fachbericht 67 (2016) Eigenverlag LANUV, ISSN 1864-3930 (Print), 2197-7690 (Internet), Link :** https://www.lanuv.nrw.de/publikationen/details?tx_cartproducts_products%5Bproduct%5D=2&cHash=00988202ead0a2c5ff79ab4782df3a71

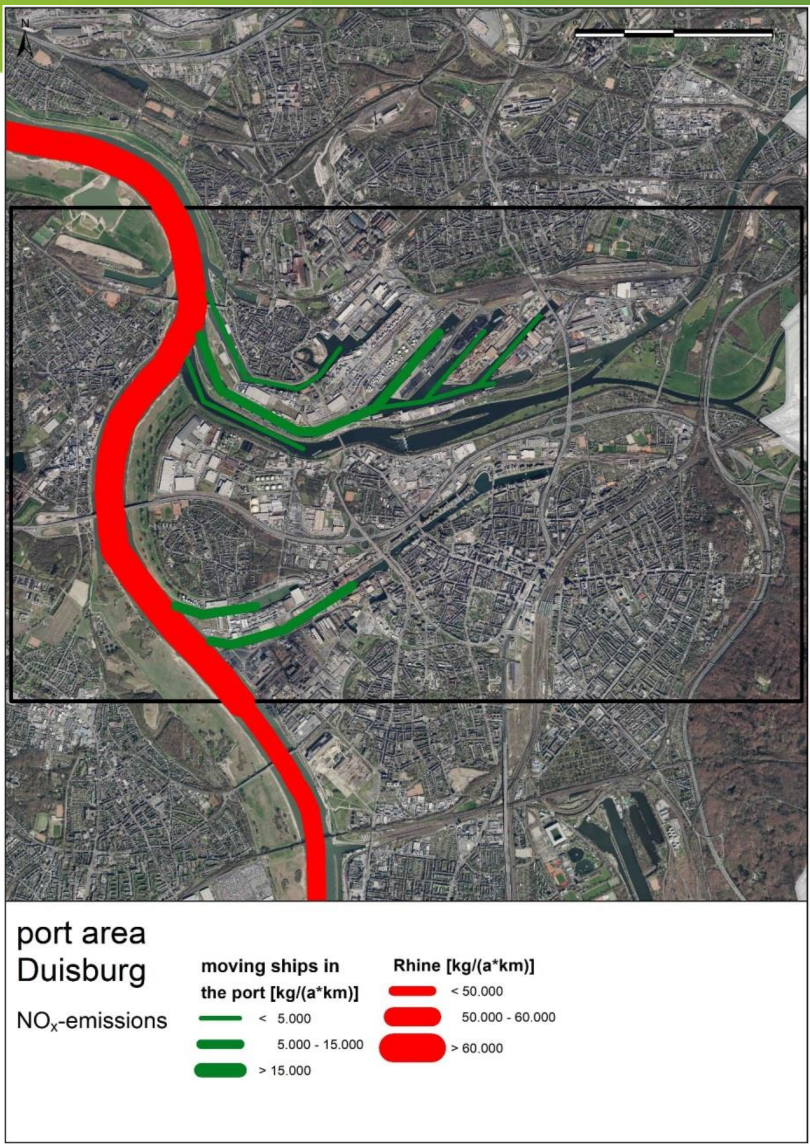


Figure 15: Representation of the emissions calculated according to the new method from ships sailing on the Rhine and in the port in the study area of Duisburg as line sources.

With extensive modelling of the root cause analyses for the air pollution detected in the measurement programs with the LASAT program in a 5*5 m grid, taking into account the building geometries in the port areas, the LANUV has analyzed the exact proportions of NO_X emissions from inland vessels and port operations for all measurement points in the port areas of Duisburg and Neuss. The detailed results of these modellings are compiled in the CLINSH report : *"Harbour Monitoring Part F: Root Cause Analyses for Air Quality Measurement Results in the Inland Ports of Neuss and Duisburg)"*.

2.4 Outlook and lessons learned

The measurement programmes, method developments and modelling carried out within the framework of CLINSH made it possible to obtain a very detailed clarification of the contribution of emissions from shipping traffic to air quality on the banks of the Lower Rhine and the settlement areas near the river, which has not been available before in this current level of detail.

Based on the data collected for CLINSH and the newly developed methods, it will be possible in future to better assess the effects of emissions from shipping and port operations beyond the CLINSH project, also in the course of the work on the air quality plans of the EU Air Quality Directive.

Conclusions and lessons learned:

1. **Ship emissions and air quality**

- The intensive CLINSH-monitoring of air quality in the ports of Neuss and Duisburg showed that the concentrations of NO_2 at the measuring points on the Rhine and in the port areas were significantly lower than previously assumed.
- In the area of the German-Dutch border near Bimmen-Lobith, the effect of NO_X emissions from 110,000 passing inland vessels per year on air quality could be determined directly. On the left bank of the Rhine (windward side), the ship emissions led to increases in the annual mean NO_2 concentrations up to 2 µg/m³ and on the right bank (leeward side) up to 4.6 µg/m³. The annual mean NO_2 concentrations on the leeward bank in Lobith fell from 21 µg/m³ in 2017 to 18.1 µg/m³ in 2020.
- The mean annual concentrations of the monitoring sites located near Duisburg directly on the Rhine ranged from 26 µg/m³ to 30 µg/m³ for the windward (left) bank and from 27 µg/m³ to 32 µg/m³ for the leeward (right) bank.
- All annual mean NO_2 values in the immediate vicinity of the emission source "shipping traffic on the Rhine" were thus clearly below the EU limit value of 40 µg/m³. The annual mean NO_2 concentrations at the Duisburg monitoring station decreased from 27 µg/m³ in 2018 to 21 µg/m³ in 2020. PM_{10} concentrations decreased between 19 and 23 µg/m³ in the same period.
- The modelling for the cause analysis on air pollution at the CLINSH monitoring sites in Duisburg and Neuss showed, that on the Thine a considerable influence of ship emissions on the air pollution of residential areas is generally narrowly limited to the riparian zones.
- For the areal pollution in the large cities along the Rhine at a greater distance from the river, emissions from local road traffic (main roads) play a dominant role.
- Emissions from moored and moving ships in the ports as well as from port operations only have a significant effect on air quality in their direct vicinity.

2. **Development of a new method for recording ship emissions using emission factors measured onshore.**

- With the automatic measuring stations, the NO_X emission peaks (measuring frequency 5 sec) of passing ships can be identified and quantified. The assignment to the ships is done by recording the AIS data.
- With more than 16,000 quantifications from real measurement results, it was possible to compile a catalogue of onshore emission factors for inland vessels on the Lower Rhine, classified according to vessel size, direction of travel (upstream/downstream) and speed over ground.

- With this catalogue and the recording of real ship traffic, a new method for the determination of the emissions of moving ships was developed and applied for the study area Neuss-Duisburg within the framework of CLINSH.
- The emission data is now no longer based on estimates of theoretical diesel consumption from performance/emission curves but on real measured onshore data.
- For the speed classification, speed classes were defined in steps of 1.0 m/s, which were also used as a basis for determining the emission factors. With this classification, an emission calculation can be made for any combination of direction of travel, ship speed and ship size.
- Due to traffic density, river morphology, flow conditions, current quays as well as harbour and canal entrances, the speed of the moving ships is not homogeneous and changes frequently. Since different pollutant quantities are also emitted at different speeds, the calculation of emissions and the determination of emission density for modelling should be carried out in sections, e.g. per river kilometer.
- With the acquisition and evaluation of AIS data, it is possible by using a suitable evaluation programme, to record the real ship traffic and it’s emissions with regard to ship type, ship size, direction of travel and speed over ground.
-

3. Development of a new method for recording the emissions of berthing inland vessels

- None of the CLINSH partners had an applicable method for a realistic detailed determination of the emissions of the moored ships. Therefore, a suitable method was developed by LANUV.
- The basis for this was the determination of the energy demand of moored tankers and cargo ships, the analysis of the generator composition (emission behaviour) on the inland vessels, the geo-referencing of the berths, the determination of the average berthing times and the derivation for average emission factors for "medium fleet generators".
- The energy demand for moored cargo vessels is about 2 kW, for moored tankers about 9 kW for shore-side loading and about 110 kW for on-board unloading (on-board pumps). For passenger ships, this demand varies between about 2 kW (winter rest) and 200 kW (fully occupied with passengers while the restaurant is in operation), depending on the respective sailing condition.
- The calculations of the emissions of the moored ships in the ports of Neuss and Duisburg resulted in significantly lower emission amounts of NO_X and PM_{10} than expected at the beginning of the project.
- By installing only a few shore power systems at the berths of the river cruise ships and the unloading points for tankers, a very large proportion of the emissions from the moored ships can be avoided.

3 Air quality modelling

Air quality modelling is necessary to demonstrate how emission reduction affects the air quality. Concentration levels of the modelled pollutants are an important indicator for health risks and represent important data for the socio-economic assessment in action C1. They are additionally needed to determine the impact of abatement technologies in the future. Inland shipping emissions for all urban domains have been prepared for different scenarios.

3.1 Clinsh scenario's

CLINSH developed a reference fleet inventory for 2020 and two IWT fleet development scenarios towards 2035: one **Baseline scenario** based on "autonomous" engine renewal and one scenario with accelerated emission reduction, referred to as **the CLINSH scenario.** Both scenarios are built on the same assumptions regarding market developments of transport volumes (e.g. coal, oil products) and related developments in vessel and fleet size and include a modest uptake of Zero Emission technologies. The **CLINSH scenario** thus describes a path to accelerate the reduction of air pollutant emissions in the period before large-scale uptake of zero emission solutions occurs and ahead of scheduled engine renewal to Stage V.

Assumptions for the Baseline scenario 2035

In the Baseline scenario, it is assumed that engine renewal leads to the introduction of new Stage V diesel engines. It is assumed that no other emission reduction technologies will be installed in the baseline scenario, as there are insufficient financial incentives to do so. Not taken into account in the Baseline are any effects from ambitions set in the Mannheim declaration (35% reduction of pollutants and GHG emissions in 2035), the Dutch climate agreement (150 electric drivetrains in 2030, 35-50% reduction of air polluting emissions in 2035), EU Green Deal or any other policy ambition, as policies and regulations to reach these ambitions are still in development and it thus remains uncertain how and if these targets will be reached.

Assumptions for the CLINSH scenario 2035

In the CLINSH scenario, autonomous engine renewal will lead to same amount of Stage V engines entering the fleet as in the Baseline scenario, but part of them will now not be diesel engines. The CLINSH scenario focuses on applying NOx and PM_{10} reducing measures up to 2035 to the part of the fleet that will not renew their engines autonomously between 2020 and 2035.

It is assumed that in 2035 on these ships the NO_x and PM_{10} reduction measures will have been implemented with the lowest societal costs measured over a period of 15 years. Given the uncertainties of future emission regulations an engine lifetime of 15 years is assumed, although actual lifetimes of engines and reduction techniques can be longer. Revision of the current engine or early placement of a Stage V engine can be a viable option as well, with either one of these options resulting in the lowest social costs. For each vessel category the best option is chosen, differentiated between low, medium and high fuel consumption.

The measures are taken during engine revision, assuming that engine revision will take place for all ships during this period. Ships with a zero-emission driveline are considered an option as well, but with a maximum of 150 in 2030 according to the ambition set in the Dutch Green deal, and 300 in 2035. Measures that only reduce CO_2, like biofuels, are not considered in the CLINSH scenarios as such, as they do not have a significant (positive or negative) effect on pollutant emissions as compared to their fossil fuel counterparts.

3.2 Clinsh emission factors

As it is practically impossible to carry out emission measurements that cover the total fleet in the whole West-European region over a whole year, CLINSH developed an emissions model to calculate these emissions for the reference year and for the two fleet development scenarios. Focus was put on the regions surrounding the ports of Rotterdam, Antwerp, Western Rhine-Ruhr area and Nijmegen (See figure 16). The model combines the emission factors from the on-board measurements, AIS location tracking signals of all vessels sailing in the regions under study, and the fleet inventory and development scenarios to arrive at emissions per year in the model regions.

So, CLINSH developed a method to identify the inland shipping contribution to urban air quality for different emission scenarios in the cities of Antwerp, Rotterdam, Nijmegen and the greater Duisburg area, also called the Western Rhine-Ruhr area (see Figure 16). It involves a consistent approach to derive land-based and shipping emissions to be applied in different air quality models. The approach is replicable in regions throughout Europe.

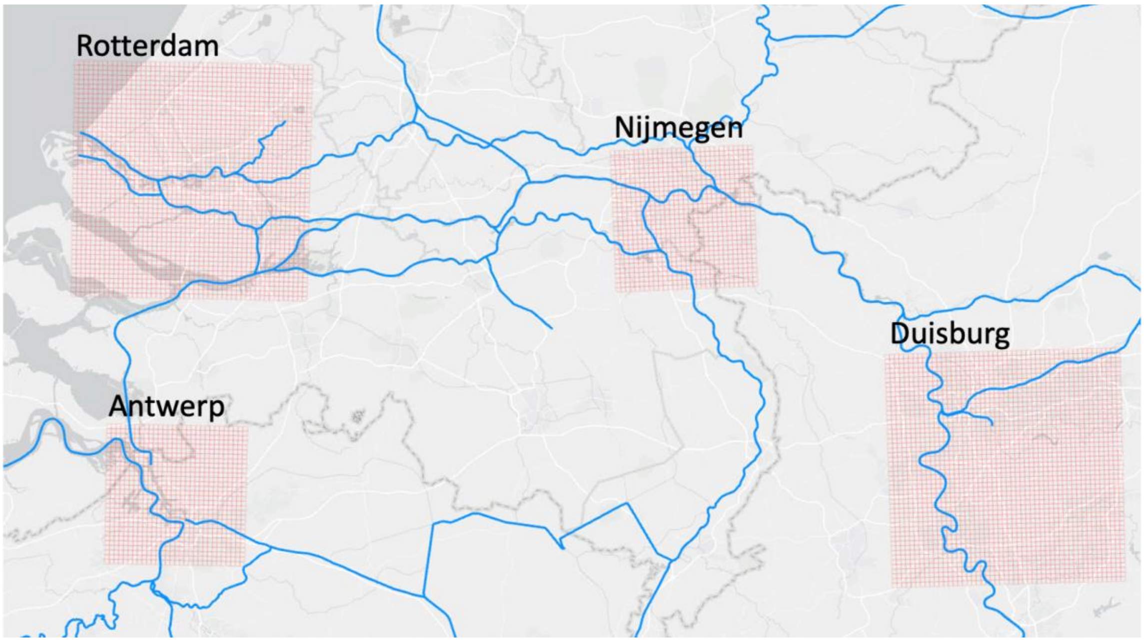


Figure 16: *Urban domain overview. The red squares illustrate the urban domains as used in the CLINSH project, while the blue lines follow inland waterways under the European Agreement on Main Inland Waterways of International Importance (AGN) by the UNECE. The map was created with ArcGIS.*

CLINSH has developed emission factor functions that relate specific emissions of NOx and PM in g/kWh to the engine loads in % for each ship in the CLINSH fleet. Next, averaged emission factor functions were created for ships belonging to the CCNR classes and abatement technologies. The resulting functions are power functions of the form $m \cdot (\%EngineLoad)^n$, determined by two parameters m and n. Further details about this approach can be found in the CLINSH report on current and future emissions[5]. The continuous NOx measurements were used to create emission factors.

[5] B3 modelled emissions of inland vessels

3.3 The air quality models

Every country has it's own modelling system used by the responsible authorities and among authorities and scientific institutes different models may be in use. Modelling atmospheric processes has been the subject of many studies, resulting in a range of models with various complexities for specific applications. Before selecting a model or a model approach, we have to assess the intended application area carefully. For CLINSH we decided to use the Eulerian grid Chemistry Transport Model EPISODE-CityChem v1.5 (Karl et al. 2019)[6] for urban-scale air quality modelling of four different areas representing the entire domain (figure 10). In the Netherlands the model OPS-Pro edition 2020 version W-5.0.0.0. was used for the local modelling of Rotterdam and Nijmegen.

In the following chapter, we will introduce the applied methods, models and datasets and present the results for the concentrations simulated with CLINSH inland shipping emission scenarios as well as their evaluation for the mentioned urban domains.

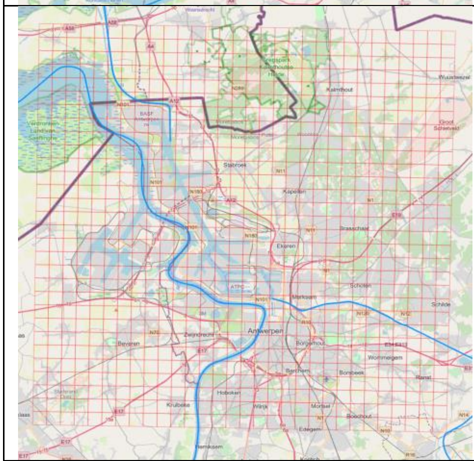
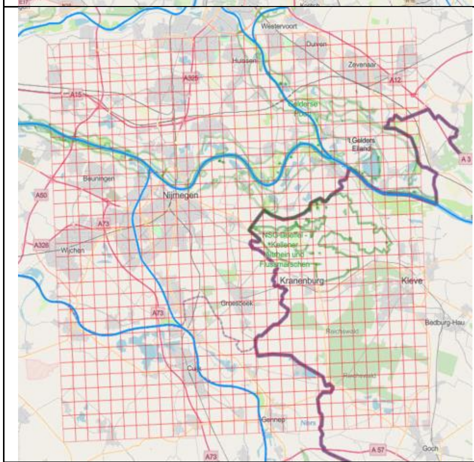
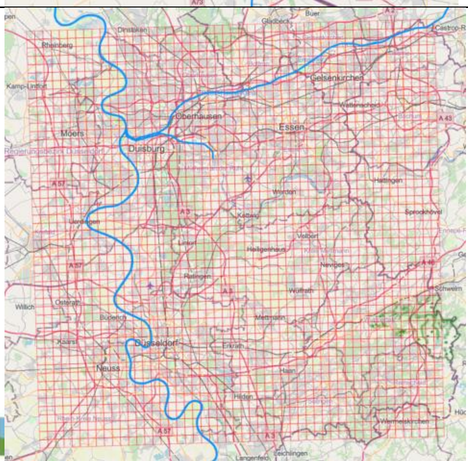
3.4 Urban air quality simulations with EPISODE-CityChem to derive inland shipping contributions

The aim of this task is the identification of inland shipping contributions to urban air quality for different CLINSH emission scenarios (S2020b, S2035b, S2035c) in the cities of Antwerp (BE), Rotterdam (NL), Nijmegen (DE/NL) and the greater Western Rhine-Ruhr area (DE) with a consistent approach to derive land-based and shipping emissions to be applied in an urban-scale Eulerian grid Chemistry Transport Model. Due to the underlying measurements and the connected derivation of real-world emission factor in the CLINSH project, this report focuses on emissions and concentrations of nitrogen oxides (NO_x), such as nitrogen monoxide (NO) and nitrogen dioxide (NO_2), as well as particulate matter (PM) with the size distributions up to 10 µm (PM_{10}) and up to 2.5 µm ($PM_{2.5}$)

In the following, we will introduce the applied methods, models and datasets before presenting results for concentrations simulated with CLINSH inland shipping emission scenarios as well as their evaluation for all urban domains as presented in Figure 16 and as specified in Table 2. Results for emissions and concentrations as presented in this report are referring to the spatial definitions of these domains.

[6] Karl, M., Walker, S.-E., Solberg, S., and Ramacher, M. O. P.: The Eulerian urban dispersion model EPISODE – Part 2: Extensions to the source dispersion and photochemistry for EPISODE–CityChem v1.2 and its application to the city of Hamburg, Geosci. Model Dev., 12, 3357–3399, doi:10.5194/gmd-12-3357-2019, 2019c. Karl, M. and Ramacher, M. O. P.: City-scale Chemistry Transport Model EPISODE-CityChem, Zenodo, 2018.

Table 1: CLINSH domain definitions for Rotterdam, Antwerp, Nijmegen and the Western Rhine-Ruhr area

	**Rotterdam** Domain extent – 50 x 50 km^2 Eulerian grid resolution – 1 x 1 km^2 Near field sub grid resolution – 100 x 100 m^2 Projection – UTM Zone 31 N
	**Antwerp** Domain extent – 30 x 30 km^2 Eulerian grid resolution – 1 x 1 km^2 Near field sub grid resolution – 100 x 100 m^2 Projection – UTM Zone 31 N
	**Nijmegen** Domain extent – 30 x 30 km^2 Eulerian grid resolution – 1 x 1 km^2 Near field sub grid resolution – 100 x 100 m^2 Projection – UTM Zone 32 N
	**Western Rhine-Ruhr area** Domain extent – 50 x 50 km^2 Eulerian grid resolution – 1 x 1 km^2 Near field sub grid resolution – 100 x 100 m^2 Projection – UTM Zone 32 N

3.4.1 Method: Air Quality Modelling System

We modelled the concentrations of atmospheric pollutants with an Air Quality Modelling System (AQMS). Figure 17 illustrates all components of an AQMS. Although there exist plenty different state-of-the-art AQMS, all AQMS consist of three different kinds of models:

1) Meteorological models are used to calculate physical properties of the atmosphere (e.g., temperature, wind speed and direction, humidity, irradiation). These meteorological parameters are needed as input in emission and chemistry transport modelling.
2) Emission models calculate the spatial and temporal variation of different pollutant emission sources.
3) Chemistry Transport Models (CTM) build upon mathematical representations of the relevant physical and chemical processes to obtain pollutant concentrations as a function of space and time for a given set of emissions and meteorological conditions (Seinfeld and Pandis, 2016).

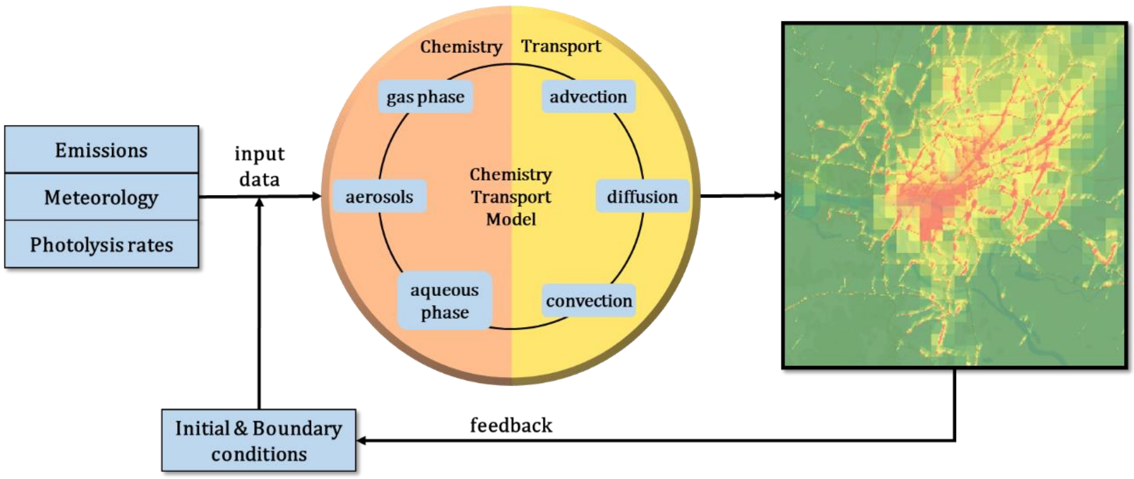


Figure 17: Schematic overview of an AQMS and CTM. Reproduced after Fig. 3 in Bieser (2011).

State-of-the-art meteorological and chemistry transport models in AQMS are Eulerian type models, which consist of many georeferenced boxes for a defined region; the so-called model grid (Sokhi et al., 2018)[7]. Each box (grid-cell) stores physical states, states of chemical species as well as changes of physical states and chemical reactions that can take place. A time step describes the duration between two states of a grid-cell. The model grid consists of a number of grid cells for a defined region. The size of uniformly sized grid boxes in a model grid is called resolution. Each grid cell is connected to its neighbors and exchanges information on matter and energy with them once at each time step. (Peters, 1995)[8]

[7] Sokhi, R. S., Baklanov, A., and Schlünzen, K.: Mesoscale modelling for meteorological and air pollution applications, ANTHEM Press, London, 1 online resource (1 volume), 2018

[8] Peters, L.: The current state and future direction of Eulerian models in simulating the tropospheric chemistry and transport of trace species: a review, Atmospheric Environment, 29, 189–222, doi:10.1016/1352-2310(94)00235-D, 1995.

In general, anEulerian grid CTM should be chosen with respect to the scale of a desired application (Baklanov and Nuterman, 2009)[9]. “A wide range of micro- and mesoscale urban features can influence the atmospheric flow, including its turbulence regime and the micro-climate, and, accordingly, modify the transport, dispersion and deposition of atmospheric pollutants within urban areas and vicinity downstream” (Sokhi et al., 2018:50)[10]. Thus, simply increasing the spatial resolution of global or regional AQMS is not sufficient to give better predictions in urban areas (Harrison, 2018)[11], due to scale-dependent processes in emission, meteorological and chemistry transport models. Important urban features for AQMS on the urban-scale such as street canyons, stacks and the urban circulation are classified as a mixture of micro- and meso-scale features, which are partially combined in the local-scale. While there exist many models that explicitly account for micro- or meso-scale features, urban-scale models are challenged to both scales, which is mostly done by parametrizing known processes.

There are a number of Chemistry Transport Models that span the global or regional scale where grid resolutions down to 4-10 km have been achieved, e.g. EMEP (Simpson et al., 2012)[12], SILAM (Sofiev et al., 2015)[13], LOTOS-EUROS (Kranenburg et al., 2013)[14], CHIMERE (Menut et al., 2013)[15], and CMAQ (Appel et al., 2017)[16]. There are also a number of Gaussian modelling systems that cover the urban and local scales over limited areas, usually individual cities, e.g. ADMS (Stocker et al., 2012)[17] and AERMOD (Cimorelli et al., 2005)[18]. In addition, there are some limited area models that combine Eulerian and Gaussian plume type models in a single system, e.g. Karamchandani et al. (2009)[19] and Karl et al. (2019).

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3.4.2 Setup – the urban air quality model EPISODE-CityChem

For this study we chose the urban-scale Eulerian grid Chemistry Transport Model EPISODE-CityChem (Karl et al. 2019), with meteorological fields derived with the meteorological module of the TAPM model (Hurley et al. 2009)[20], and land-based emissions from different sources, such as the European inventories CAMS-Reg-AP[21] and E-PRTR (https://industry.eea.europa.eu/)[22], while sea-going- and inland-shipping emissions are derived within the CLINSH project.

The EPISODE-CityChem model combines a 3-D Eulerian grid model with sub-grid Gaussian dispersion models to resolve pollutant dispersion in proximity of point sources and line sources. On the Eulerian grid, time-dependent 3-D concentration fields of the pollutants are calculated by solving the advection/-diffusion equation with terms for chemical reactions, dry deposition and wet deposition, and area emissions. The hourly 2-D and 3-D fields of meteorological variables and the hourly 2-D fields of area emissions are given as input to the model with the spatial resolution of the Eulerian grid. For this study, we defined a Eulerian grid with a spatial resolution of 1 km, while the sub-grid for near field dispersion was defined with a spatial resolution of 100 m.

As introduced, we applied prognostic meteorological fields from the meteorological component of the coupled meteorological and chemistry transport model TAPM. To drive the meteorological module of TAPM, we applied three-hourly synoptic scale ECMWF ERA5 reanalysis ensemble means for 2019 on a longitude/latitude grid at 0.3-degree grid spacing. The meteorological fields simulated with TAPM have a horizontal resolution of 1x1 km^2 and a vertical resolution of 30 layers with different heights, following the EPISODE-CityChem vertical layer structure.

To account for the background air concentrations, we applied hourly Copernicus Atmospheric Monitoring Services (CAMS) ensemble reanalysis (http://www.regional.atmosphere.copernicus.eu) for the year 2019 and for the pollutants carbon monoxide (CO), ammonia (NH3), NMVOC, NO, NO_2, O_3, peroxyl nitrates (PANS) particulate matter (PM_{10}, $PM_{2.5}$) and SO_2. The CAMS regional ensemble is based on seven state-of-the-art numerical air quality models developed in Europe. The spatial resolution of the regional forecast is 0.1 x 0.1 degrees for whole Europe, with nine vertical levels, extending from the surface up to 500 hPa, and the time resolution is one hour. The CAMS forecast concentrations are downloaded and interpolated to the horizontal and vertical resolution of the domain, to be considered at the lateral and vertical borders of the urban domains in EPISODE-CityChem simulations.

In EPISODE-CityChem, emissions from point sources are added onto the Eulerian grid concentration during each time step. Emissions from line sources are added to the grid concentrations following a procedure described in more detail in Hamer et al. (2019)[23]. The combination of a Eulerian grid model with sub-grid Gaussian dispersion models allows for calculation of ground-level concentrations near pollution sources with high spatial resolution. Moreover, a simplified street canyon model (SSCM) is

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[23] Hamer, P.D.; Walker, S.-E.; Sousa-Santos, G.; Vogt, M.; Vo-Thanh, D.; Lopez-Aparicio, S.; Ramacher, M.O.P.; Karl, M. The urban dispersion model EPISODE. Part 1: A Eulerian and subgrid-scale air quality model and its application in Nordic winter conditions. *Geosci. Model Dev. Discuss.* **2019**, 1–57, doi:10.5194/gmd-2019-199

part of EPISODE-CityChem for better treatment of pollutant dispersion in street canyons in comparison to models without SSCM. The SSCM module computes concentrations for the receptor points that are located in street canyons. The SSCM is based on the Open Street Pollution Model (OSPM) but uses simplified street canyon geometry.

To account for all relevant emission sources in the study domain, emission data containing sector-specific and geo-referenced yearly emission totals created with a consistent approach are processed with the EPISODE-CityChem interface for emission pre-processing, the Urban Emission Conversion Tool (UECT). UECT creates hourly varying emission input for point sources, line sources and area source categories using sector specific temporal profiles and vertical profiles, based on annual totals of emissions. Temporal profiles from the SMOKE-EU model are applied in UECT.

3.4.3 Emissions – inland shipping, sea-going ships & land-based

As introduced, it is necessary to provide spatial and temporal information on all relevant emission sources to run an AQMS. To prepare the emissions, we have distinguished between emissions from land-based sources, sea-going ships and inland shipping emissions.

3.4.3.1 CLINSH inland-shipping emissions

Inland shipping emissions for all urban domains have been prepared in WPXY for different scenarios. These emissions have been prepared as an input for the EPISODE-CityChem model domains. The line emissions have been aggregated to area emissions with horizontal grid resolution of 1x1 km^2. It is assumed that all emissions are released in the first vertical layer (up to 17.5 m). The temporal profile of all emissions is based on real-time AIS data instead of generic profiles. Table 3 shows annual emission totals for 2019 as prepared for the urban domains. It has to be taken into account that the presented emission in Table 3 totals are not representing emission totals within the municipal or federal boundaries of each city, but are emission totals for the domain areas as defined in Table 2. Depending on the size and the location of each domain, the emission totals will change.

Table 3: CLINSH scenario inland shipping emissions of nitrogen oxides (NO_x) and particulate matter (PM) in tons per year applied in all urban domains in 2019. S2020b: reference scenario 2020, S2035b: baseline scenario 2035, S2035c: CLINSH scenario 2035

	Rotterdam		**Nijmegen**		**Antwerp**		**Western Rhine-Ruhr area**	
	NO_x [t/a]	PM [t/a]	NO_x [t/a]	PM [t/a]	NO_x [t/a]	PM [t/a]	NO_x [t/a]	PM [t/a]
Year 2019								
S2020b	2680	90	1320	40	970	30	2050	60
S2035b	2072	69	971	28	748	27	1588	46
S2035c	748	25	275	4	270	13	449	10

3.4.4 Emissions from sea-going ships

The emissions from sea-going ships for the city of Antwerp have been provided as annual totals by the Port of Antwerp for the year 2019 and were resampled to the urban domain grid of Antwerp with a horizontal resolution of 1 km^2. The temporal distribution from annual to hourly values was done with EUROS-LOTOS time profiles.

The emissions from sea-going ships for the city of Rotterdam were created with the Modular Ship Emission Modeling System (MoSES) in version 1.0, using AIS data for the year 2019 in a bottom-up approach (Schwarzkopf et al., 2021)[24]. The emission inventory was created on a grid with the resolution of 0.17° (North - South, approx. 3.3 km), 0.03° (East - West, approx. 12 km) and then resampled to the urban domain grid of Rotterdam with a horizontal resolution of 1 km^2. It contains the gas species CO_2, NO_X, SO_2, CO, CH_4, NMVOC, N_2O and the aerosol species SO_4, SO_4 x H_2O, Black Carbon (BC), Primary Organic Aerosols (POAs) and Mineral Ash (MA), which also are aggregated as PM.

Table 4 shows annual emissions totals for sea-going ships in Rotterdam and Antwerp in 2019 as used in the EPISODE-CityChem setup.

Table 4: Annual emission totals for sea-going ships for the urban domains Rotterdam and Antwerp.

	Rotterdam		**Antwerp**	
	NO_x [t/a]	PM [t/a]	NO_x [t/m]	PM [t/a]
2019	8119,1	279,8	7828,5	219,2

3.4.5 Land-based emissions

Land-based emissions were prepared with a consistent approach for all urban domains. This was done to:

(1) achieve full comparability between all areas of interest, and

(2) to demonstrate the technical possibility of investigating inland shipping impacts in any area of interest based on scenarios and emissions developed in the CLINSH project,

(3) without the need of city-specific emission inventories provided by municipalities or federal agencies.

The applied approach to arrive at high-resolution area emissions, as well as point and line source emissions for city-scale air quality modeling, follows a generalized framework described in Figure 18.

[24] Hamer, P.D.; Walker, S.-E.; Sousa-Santos, G.; Vogt, M.; Vo-Thanh, D.; Lopez-Aparicio, S.; Ramacher, M.O.P.; Karl, M. The urban dispersion model EPISODE. Part 1: A Eulerian and subgrid-scale air quality model and its application in Nordic winter conditions. *Geosci. Model Dev. Discuss.* **2019**, 1–57, doi:10.5194/gmd-2019-199

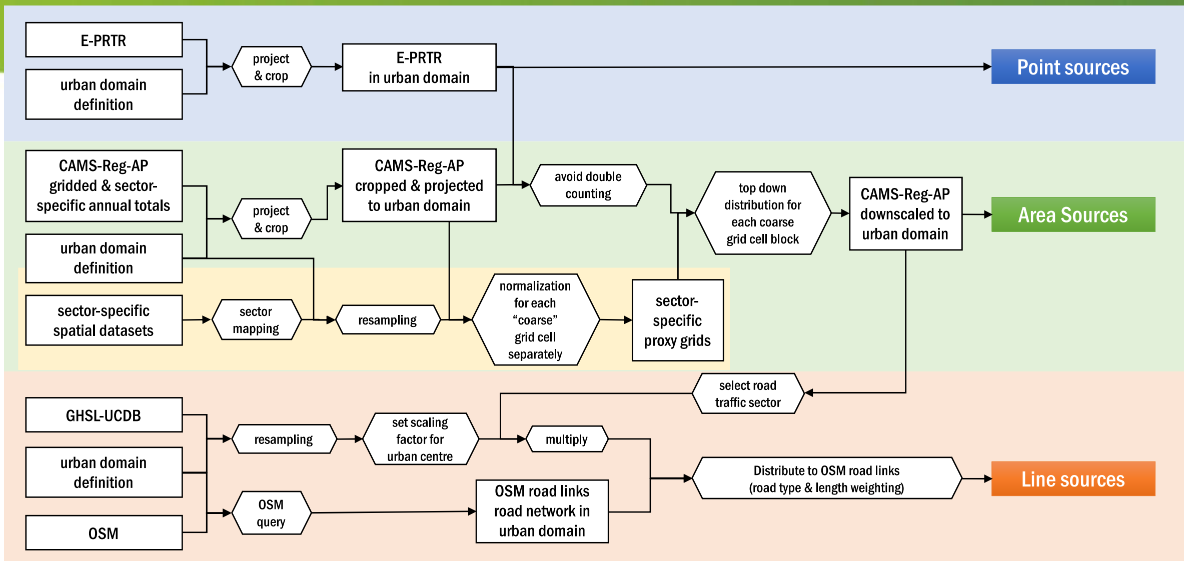


Figure18: Schematic representation of the approach for downscaling regional emission inventories to arrive at urban-scale emission inventories including point, area and line sources.

This framework (submitted for publication) can be applied to any urban region in Europe. Based on an urban domain definition, in line with the requirements of a city-scale air quality model, sector-specific spatial proxies are prepared based on publicly available datasets to distribute CAMS-Reg-AP and E-PRTR emission datasets to area, point and line sources. Table 5 introduces anthropogenic activities based on SNAP or GNFR classification, which are allocated to the appropriate proxies, such as population density, land type categories (e.g. industrial, agriculture) and road networks.

Table 5: The spatial proxies (and their origin) used to disaggregate each anthropogenic activity (expressed as source sectors in SNAP and GNFR) in the proposed downscaling framework.

Anthropogenic activity (Source sector)	**Proxy (dataset source)**
Public Power and Refineries (SNAP 1 or GNFR A)	Polygons hosting Public Power installations (E – PRTR and CLC 2018) combined with Land type characterized as 'Industry' (CLC 2018)
Residential Heating (SNAP 2 or GNFR B)	(Residential) population Density (GHS-POP 2015)
Fossil Fuel Production and Fugitive (SNAP 5 or GNFR D)	Land type characterized as 'Industry' (CLC 2018)
Solvent and other use production (SNAP 6 or GNFR E)	(Residential) population Density (GHS-POP 2015)
Road emissions (SNAP 7: 71,72,73,74,75 or GNFR F)	Major Road Network (OSM) consisting of highways, trunks, primary & secondary roads and their links
Non-Road Mobile emissions (SNAP8): (Shipping) (GNFR G))	A superposition of Global shipping routes (CIA 2013) and Land type characterized as 'Ports' (CLC 2018)
Non-Road Mobile emissions (SNAP8): Aviation (GNFR H)	Land type characterized as 'Airports' (CLC 2018)
Non-Road Mobile emissions (SNAP8): Off road machinery (GNFR I)	Land type characterized as 'Non-Road Mobile Sources' (CLC 2018) relevant to agricultural, industrial and construction activities

Waste Treatment (SNAP 9 or GNFR J)	Polygons hosting waste management installations (E - PRTR and CLC 2018) combined with Land type characterized as 'Agriculture' (CLC 2018) to allocate open waste.
Agriculture (SNAP 10 or GNFR K, GNFR L)	Land type characterized as 'Agriculture' (CLC 2018)
Industrial Combustion and Processes (SNAP 34 or GNFR B)	Polygons hosting installations of mineral or chemical industries and of production (and processing) of wood, paper, metals, animal and vegetable (E - PRTR and CLC 2018) combined with Land type characterized as 'Industry' (CLC 2018)

To create a point source emission inventory, the E-PRTR emissions register is applied to get the annual total emission values as well as their spatial location and sectoral information. To create area source emissions, CAMS- regional emissions are combined with spatial datasets that are mapped to be used as sector specific spatial downscaling proxies. To account for line sources, which are mainly emission sources from the road transport sector, CAMS emissions of the road transport are downscaled to area sources with the introduced procedure and distributed to road links derived from OpenStreetMap (OSM).

Although the consistent approach to downscale regional emissions to the urban-scale might not be able to achieve the same level of accuracy as bottom-up emission inventories or emission inventories compiled and reviewed by municipalities, local or federal agencies, it shows good agreement with emission totals, their spatial distribution and when applied in an urban-scale CTM (Ramacher et al. 2021, in review). Additionally, the goal of this WP is to identify and compare the impact of inland shipping emissions in different scenarios between multiple cities, of which some have detailed emission inventories, while some have not. To achieve full comparability, to be consistent, we decided to apply the same approach for all cities to create land-based emission inventories, whether there are detailed emission inventories available or not.

In this study, we applied the introduced downscaling approach to create emission inventories for all urban areas with a spatial resolution of 1 km^2. We applied the CAMS-Reg-AP v3.1 dataset and the E-PRTR database for the year 2016, which is the latest available year. Due to relatively slowly changing annual emissions of land-based emissions and the focus on inland shipping emissions, and their impact on the overall air quality in the year 2019, it is possible to obtain qualitative findings without applying scaling factors for land-based emissions to achieve emissions for 2019. Nevertheless, as soon as emission inventories become available for more recent years, these should be applied.

Table 6 shows the annual total emissions for NO_x and PM_{10} by SNAP sector classification as derived with the introduced downscaling approach within each urban domain. Additionally, the type of source (asrc = area source, psrc = point source, lsrc = line source) is given. Although displayed in table 5, SNAP8 was not used as an input in the urban air quality simulations to avoid double counting of inland and sea-going shipping emissions. Instead, shipping in SNAP8 has been replaced by the introduced sea-going shipping emissions in Rotterdam and Antwerp as well as the introduced CLINSH scenario inland shipping emissions for all urban domains. Other mobile sources than shipping in SNAP8 have been taken into account.

Table 6: Annual total emissions in kt/a for all urban domains as derived from downscaling and distributing CAMS-Reg-AP and E-PRTR emission inventories for the year 2016.

SNAP	source type	Rotterdam [kt/a]		Nijmegen [kt/a]		Antwerp [kt/a]		Western Rhine-Ruhr area [kt/a]	
		NO_x	PM_{10}	NO_x	PM_{10}	NO_x	PM_{10}	NO_x	PM_{10}
SNAP1	psrc	6.73	0.18	0.37	-	5.63	0.12	13.39	
SNAP1	asrc	-	0.03	0.64	0.03	0.15	0.04	0.02	0.66
SNAP2	asrc	1.75	0.12	0.48	0.08	0.70	0.53	2.11	0.42
SNAP3	psrc	0.57	0.06	-	-	0.34	-	11.89	2.63
SNAP3	asrc	3.27	0.93	0.11	0.16	4.82	0.77	0.71	2.18
SNAP4	psrc	1.98	-	-	-	5.22	-	1.51	
SNAP4	asrc	-	0.25	0.03	0.04	-	0.19	1.64	1.20
SNAP5	asrc	0.01	-	-	-	0.03	0.01	0.02	0.00
SNAP6	psrc	1.72	0.07	-	-	0.82	-	2.42	
SNAP6	asrc	-	0.09	0.04	0.04	-	0.04	-	0.50
SNAP7	lsrc	14.70	1.37	2.36	0.22	6.68	0.59	21.42	2.22
SNAP8*	asrc	17.33*	0.99*	2.80*	0.16*	12.75*	0.77*	1.09*	0.06*
SNAP10	asrc	1.89	0.24	0.36	0.21	0.41	0.18	2.09	0.48
Total [kt/a]		**49.97**	**4.33**	**7.19**	**0.95**	**37.55**	**3.24**	**58.30**	**10.36**

* shipping in SNAP 8 not used in simulations with EPISODE-CityChem, replaced with sea-going and inland shipping emissions for 2019.

As introduced, the annual total emissions are processed with the Urban Emission Conversion tool (UECT), to create area emission input files for EPISODE-CityChem. During processing with UECT monthly, weekly and daily time profiles are applied for each sector separately to distribute the annual emissions to hourly emission rates.

3.4.6 Results – urban air quality simulations

To identify the impact of inland shipping emissions on the overall air quality in Rotterdam, Nijmegen, Antwerp and Western Rhine-Ruhr area, we performed a series of different simulations for the months January and July 2019 with the described datasets. While the meteorological input from TAPM for the year 2019, the regional boundary conditions from CAMS for the year 2019, the land-based emissions for the year 2016 and the emissions from sea-going ships for the year 2019 were kept constant, the inland shipping emissions as derived in the CLINSH project have been replaced for each scenario. Additionally, we ran simulations without inland shipping emissions, to identify the current impact of inland shipping on the overall air quality situation.

The first task was to identify the performance of the air quality simulations for each domain, by comparing a base run against available measurements of pollutants. Therefore, we defined the S2020b scenario as base run, which shall reflect the current situation in 2019. The second task was to identify the impact of inland shipping by performing simulations with and without inland shipping emissions for scenario S2020b. The third task was the identification of reduction potentials given by the future scenarios S2035b and S2035c, compared to the base scenario S2020b.

3.4.6.1 Evaluation of air quality simulations

To evaluate the air quality simulations we compared hourly, daily and monthly averaged air pollutant concentrations of PM_{10} and NO_2 against available measurements. A full list of all stations we applied in the valuation can be found in table 6. All stations are listed under their European air quality database

(AirBase) code. We decided to evaluate PM_{10} and NO_2, because these pollutants are the fractions of PM and NO_x, which have been regulated the longest under the EC Air Quality Directive 2008/50/EC.

In the Western Rhine-Ruhr domain two continuous measurement sites (DENW382 and DENW381) were operated under the CLINSH project. For these stations, detailed evaluations will be done.

Table 7: List of Airbase stations applied to evaluate pollutant concentrations in all urban domains.

station code	site type	site area	pollutants measured
Rotterdam			
NL00404	background	urban	NO, NO_2, O_3, PM_{10}, $PM_{2.5}$
NL00418	background	urban	NO, NO_2, O_3, PM_{10}, $PM_{2.5}$
NL00437	background	rural	NO, NO_2, O_3, PM_{10}
NL00442	background	urban	NO, NO_2, O_3, PM_{10}
NL00445	traffic	urban	NO, NO_2, PM_{10}
NL00446	background	suburban	NO, NO_2, O_3, PM_{10}
NL00448	traffic	urban	PM_{10}, $PM_{2.5}$
NL00449	traffic	urban	NO, NO_2, O_3, PM_{10}, $PM_{2.5}$
NL00485	industrial	urban	NO, NO_2, O_3, SO_2, PM_{10}
NL00487	traffic	urban	NO, NO_2, PM_{10}, $PM_{2.5}$
NL00488	background	urban	NO, NO_2, PM_{10}, $PM_{2.5}$
NL00489	traffic	urban	NO, NO_2, O_3, PM_{10}, $PM_{2.5}$
NL00491	traffic	urban	NO, NO_2, PM_{10}, $PM_{2.5}$
NL00493	traffic	urban	NO, NO_2, O_3, PM_{10}
NL00494	background	urban	NO, NO_2, O_3, PM_{10}, $PM_{2.5}$
NL00495	industrial	urban	NO, NO_2, O_3, SO_2, PM_{10}, $PM_{2.5}$
NL00496	industrial	rural	NO, NO_2, O_3, SO_2, PM_{10}, $PM_{2.5}$

Nijmegen			
NL00741	traffic	urban	NO, NO_2, PM_{10}, $PM_{2.5}$
NL00742	background	urban	NO, NO_2, O_3, $PM_{2.5}$
Antwerp			
BELAL01	industrial	suburban	PM_{10}, $PM_{2.5}$, NO_2
BELAL02	industrial	rural	PM_{10}, $PM_{2.5}$
BELAL03	industrial	rural	PM_{10}, $PM_{2.5}$
BELAL05	industrial	rural	PM_{10}, $PM_{2.5}$
BELHB23	industrial	suburban	PM_{10}, $PM_{2.5}$, NO_2, SO_2
BELR833	industrial	rural	NO_2
BELSA04	industrial	rural	PM_{10}, $PM_{2.5}$
BETM802	industrial	suburban	PM_{10}, $PM_{2.5}$, NO_2
BETR801	background	urban	PM_{10}, $PM_{2.5}$, NO_2, O_3, SO_2
BETR802	traffic	urban	PM_{10}, $PM_{2.5}$, NO_2
BETR803	background	urban	PM_{10}, $PM_{2.5}$, NO_2
BETR805	traffic	urban	PM_{10}, $PM_{2.5}$, NO_2
BETR811	background	suburban	PM_{10}, $PM_{2.5}$, NO_2, O_3
BETR817	background	suburban	PM_{10}, $PM_{2.5}$, NO_2
BETR820	background	suburban	NO_2, SO_2
BETR823	background	suburban	PM_{10}, $PM_{2.5}$, NO_2
BETR830	industrial	rural	NO_2
BETR831	industrial	rural	PM_{10}, $PM_{2.5}$, O_3, SO_2
BETR892	industrial	rural	NO_2, SO_2
BETR893	industrial	suburban	NO_2, SO_2
BETR897	industrial	suburban	NO_2, SO_2
Western Rhine-Ruhr area			
DENW021	industrial	urban	PM_{10}, SO_2, O_3, NO, NO_2
DENW040	background	suburban	PM_{10}, SO_2
DENW082	traffic	urban	PM_{10}, NO, NO_2
DENW338	industrial	urban	PM_{10}, SO_2, NO, NO_2
DENW382	background	CLINSH	PM_{10}, NO, NO_2
DENW247	background	suburban	O_3, NO, NO_2
DENW024	background	urban	PM_{10}, SO_2, NO, NO_2
DENW022	background	suburban	NO, NO_2
DENW042	background	urban	PM_{10}, O_3
DENW116	industrial	suburban	NO, NO_2
DENW071	background	urban	PM_{10}, O_3, NO, NO_2
DENW381	background	CLINSH	PM_{10}, NO, NO_2
DENW078	background	suburban	PM_{10}, O_3, NO, NO_2
DENW080	background	suburban	PM_{10}, O_3, NO, NO_2
DENW038	background	urban	PM_{10}, O_3, NO, NO_2
DENW112	traffic	urban	PM_{10}, NO, NO_2
DENW134	traffic	urban	PM_{10}, NO, NO_2
DENW043	traffic	urban	PM_{10}, NO, NO_2
DENW208	traffic	urban	PM_{10}, NO, NO_2
DENW188	traffic	urban	PM_{10}, NO, NO_2
DENW206	traffic	urban	PM_{10}, NO, NO_2
DENW189	traffic	urban	PM_{10}, NO, NO_2
DENW034	industrial	urban	PM_{10}, SO_2, O_3, NO, NO_2
DENW114	background	urban	PM_{10}, O_3, NO, NO_2

In the following we present an overview of the most import statistical indicators for evaluating simulated air pollutant concentrations against measurements for NO_2 (Table 7) and PM_{10} (Table 8) by year and type of station. Therefore, we aggregated all hourly values by station type and area and applied only pairwise available hourly values.

Table 8: Evaluation statistic of hourly simulated vs. hourly measured values of NO_2 at all available stations.

area	type	year	n	FAC2	MB	NMB	RMSE	r	IOA
Rotterdam									
n.a.	industry	2019	26079	0.57	-5.7	-0.23	19.1	0.45	0.54
rural	background	2019	43220	0.74	-2.5	-0.14	10.6	0.67	0.62
suburban	background	2019	43512	0.75	-5.4	-0.22	15.5	0.66	0.65
urban	background	2019	8646	0.75	0.3	-0.01	14.9	0.64	0.64
urban	traffic	2019	43220	0.71	-2.9	-0.09	18.7	0.58	0.57
Nijmegen									
urban	background	2019	8553	0.82	-2.4	-0.11	11.7	0.63	0.63
urban	traffic	2019	8553	0.85	-1.9	0.05	15.1	0.55	0.56
Antwerp									
n.a.	industrial	2019	68036	0.81	-3.8	-0.14	0.4	0.58	0.56
suburban	background	2019	15327	0.73	-0.7	-0.04	0.3	0.61	0.65
urban	background	2019	68036	0.85	-3.1	-0.11	0.3	0.58	0.56
urban	traffic	2019	15327	0.69	-11.6	-0.31	0.3	0.62	0.49
Western Rhine-Ruhr area									
n.a.	industry	2019	29063	0.63	3.9	0.14	23.4	0.26	0.26
suburban	background	2019	42518	0.52	-8.1	-0.31	20.1	0.23	0.34
urban	background	2019	29063	0.65	-1.3	-0.06	19.6	0.41	0.37
urban	traffic	2019	42518	0.64	-13 9	-0.38	23.1	0.43	0.41

Table 9: Evaluation statistic of hourly simulated vs. hourly measured values of PM_{10} at all available stations.

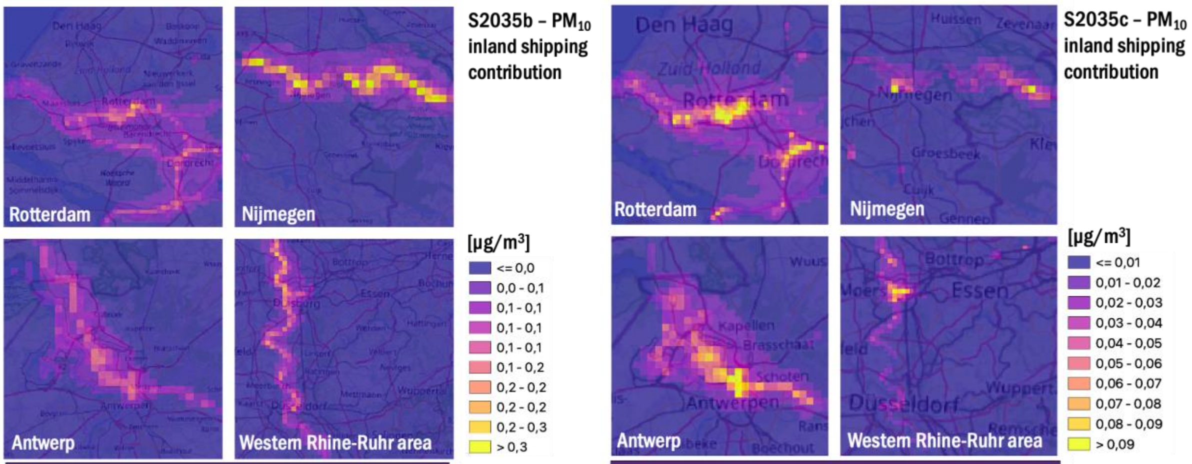
area	type	year	n	FAC2	MB	NMB	RMSE	r	IOA
Rotterdam									
n.a.	industry	2019	25108	0.76	-6.1	-0.39	11.3	0.51	0.51
rural	background	2019	8670	0.67	-4.3	-0.24	10.6	0.59	0.56
suburban	background	2019	42424	0.68	-3.5	-0.22	12.2	0.42	0.53
urban	background	2019	8705	0.74	-5.1	-0.21	11.3	0.56	0.55
urban	traffic	2019	42845	0.75	-5.9	-0.27	11.7	0.48	0.54
Nijmegen									
urban	traffic	2019	8646	0.70	-4.4	-0.21	17.1	0.42	0.56
Antwerp									
n.a.	industrial	2019	69533	0.87	-6.2	-0.27	12.1	0.65	0.58
suburban	background	2019	17246	0.93	-4.3	-0.20	9.6	0.74	0.64
urban	background	2019	69533	0.90	-6.2	-0.26	10.9	0.72	0.59
urban	traffic	2019	17246	0.85	-8.4	-0.32	14.5	0.70	0.58
Western Rhine-Ruhr area									
n.a.	industry	2019	23295	0.71	0.3	0.02	21.3	0.31	0.25
suburban	background	2019	53621	0.80	-3.5	-0.17	10.1	0.40	0.48
urban	background	2019	23295	0.79	-4.1	-0.23	12.9	0.37	0.53
urban	traffic	2019	53621	0.69	-8.9	-0.39	14.5	0.38	0.39

As indicated in Figures 19 and 20, the reduction potential in the S2035c appears to be much higher than in S2035b (compared to S2020b). In Figures 11 the reduction potential of the CLINSH S2035c inland shipping scenario is mapped for Rotterdam, Nijmegen, Antwerp and the Western Rhine-Ruhr area.

While in scenario S2035b mean reductions of ca. 20-25% for the urban domains are simulated, the S2035c scenario shows a reduction potential of 70-76% for NO_2 inland shipping emission impacts in 2035. For PM_{10} the reduction potentials in S2035b 23-27% for Rotterdam, Antwerp and the Western Rhine-Ruhr area, while they are up to 33% for Nijmegen. In S2035c the reduction potentials for Antwerp and Rotterdam are 61% and 66%, while for the Western Rhine-Ruhr area the reduction potential is up to 85% and for Nijmegen it is almost 90%.

In annex 6 more results, simulated for the months January and July, can be found.

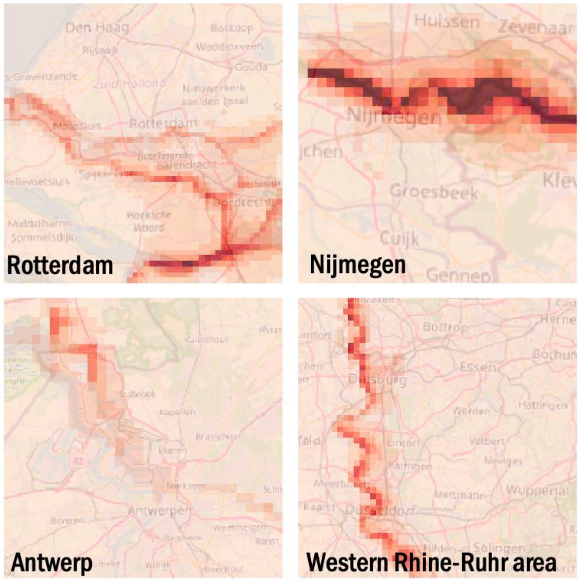
In general, there exists a high reduction potential for both pollutants in all urban domains, when simulating the S2035c scenario as developed within the CLINSH project.



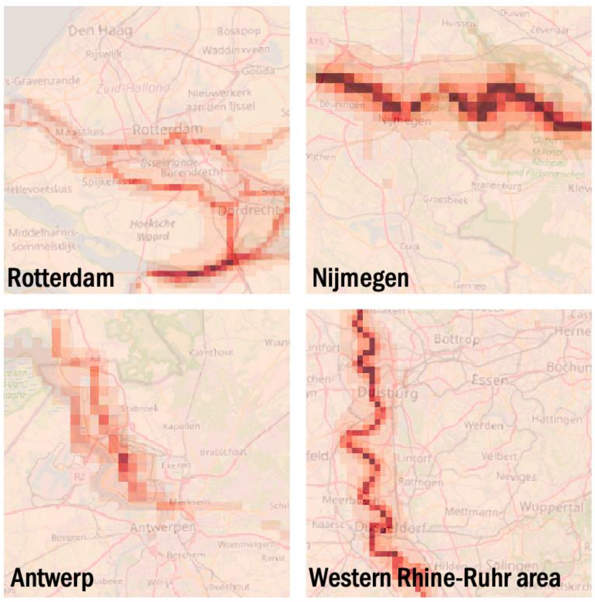
domain	Mean [µg/m³]	Max [µg/m³]
Rotterdam	0,03	0,33
Nijmegen	0,03	0,55
Antwerp	0,02	0,24
Western Rhine-Ruhr area	0,02	0,30

domain	Mean [µg/m³]	Max [µg/m³]
Rotterdam	0,013	0,25
Nijmegen	0,005	0,11
Antwerp	0,011	0,13
Western Rhine-Ruhr area	0,004	0,08

Figure 19: PM_{10} Inland shipping contribution in scenario S2035b and S2035c.



domain	Mean red. [%] S2035b	Mean red. [%] S2035c
Rotterdam	-25	-72
Nijmegen	-23	-76
Antwerp	-22	-70
Western Rhine-Ruhr area	-20	-76



domain	Mean red. [%] S2035b	Mean red. [%] S2035c
Rotterdam	-25	-66
Nijmegen	-33	-89
Antwerp	-23	-61
Western Rhine-Ruhr area	-27	-85

Figure 20: Reduction potentials due the CLINSH scenario S2035c.

3.4.8 Discussion of results

The application of the presented air quality modeling system EPISODE-CityChem in the urban domains Rotterdam, Antwerp, Nijmegen and Western Rhine-Ruhr area led to the identification of inland shipping impacts in a scenario representing the current conditions, as well as two future scenarios following the outcomes of the CLINSH project (B3 and D.

The presented modeling system is intended as a tool that can be applied to any region in Europe using the same publicly available input data for meteorology, boundary conditions and emissions. This allows for a direct comparison between different areas based on the same assumptions and datasets. Therefore, the presented approach is considered to be a consistent approach.

Nevertheless, such a consistent modeling chain also implies some shortcomings. Due to the application of harmonized European datasets, city-specific emission inventories are not applied in the modeling chain. Therefore, the accuracy of modelled values compared to observed values might be lower. This needs to be taken into account, in the choice of this modeling chain for a suitable application. While it is possible to achieve comparable qualitative results, such as the contribution of a specific emission sector in different cities or regions, the presented modeling chain and its results in this report are not sufficient for air quality reporting. To suffice for air quality reporting the air quality simulations performed within the CLINSH project would need in-depth analyses and city-specific inventories and parametrization, which is generally possible but out of the scope of this project.

Additionally, there are some technical limitations, which come with the choice of an Eulerian grid Chemistry Transport model. The mean contributions of inland shipping as given in the tables in Figures 5, 6, 7 and 8 seem to be very low. But in the interpretation of these means it has to be taken into account that these means represent a mean of all grid cells of the 100m receptor raster in each domain and not only in the proximity or the area of influence of inland shipping activities. Thus, also areas with very low or non-existent contributions of shipping are taken into account in the calculation of the mean values. The mean concentrations arising from inland shipping are considerably higher in the proximity of the source.

Another important aspect that needs to be considered in the result interpretation is the grid cell size (resolution). Inland shipping emissions are treated as area sources with a size of $1km^2$ in each modeling domain. Therefore, it is likely to happen, that high emissions at/over the shipping lanes or port areas become diluted and thus, the resulting concentrations calculated at the 100m receptor raster are relatively low. Such dilution effects, which are an inherent part of Eulerian grid chemistry transport models can be avoided with e.g. Lagrangian or Gaussian plume modeling approaches (e.g. the OPS model), which allow for much higher resolutions but mostly lack the chemical transformation of pollutants.

When comparing the reduction potentials for inland shipping emissions, with reduction potentials for the simulated concentrations, it becomes evident, that there are no linear connections. This is due to consideration of atmospheric and pollutant chemistry in the EPISODE-CityChem model: secondary particle formation, deposition processes and photochemistry are the main drivers for PM_{10} and NO_2 formation and degradation in the atmosphere. Thus, it is clearly necessary to apply air quality modeling systems such as EPISODE-CityChem to take into account all relevant processes that can influence air quality levels.

3.5 The OPS model to derive inland shipping contributions

Inland shipping emissions for all urban domains were prepared in B3 for the different scenarios as an input for the different models. The line emissions were aggregated to area emissions with horizontal grid resolution of 1x1 km^2. The model selected to calculate the effect of the scenarios on the air quality in Rotterdam and Nijmegen is OPS-Pro ((Operational Priority Substances) edition 2020 version W-5.0.0.0. (https://www.rivm.nl/documenten/uitgebreide-modelbeschrijving-van-ops-versie-5000.

3.5.1 The OPS-Pro model

OPS simulates the atmospheric process sequence of emission, dispersion, transport and deposition. The main purpose of the model is to calculate the concentration and deposition of pollutants (e.g. particulate matter, acidifying compounds like SO_2, NO_x and NH_3) for the Netherlands using a high spatial resolution (typical 1 x 1 km^2). The model is, however, set up as a universal framework supporting the modelling of other pollutants such as fine particles and persistent organic pollutants. Eulerian models can suffer from large errors on a local scale, due to numerical dispersion. Eulerian models using nested grids should, to a certain extent, be applicable. At the time in the Netherlands it was decided to develop the OPS model for reporting air quality and not to use a Eulerian model. OPS uses a method for calculating long-term averages by arranging situations having similar properties into classes and then calculating representative concentrations for each of the classes. The average value will then follow from a summation of all concentrations, weighted with their relative frequencies of occurrence. OPS uses a classification based on transport distance, wind direction and a combination of atmospheric stability and mixing height. The approach used for the OPS-model can be classified as a long-term climatological trajectory model which treats impacts of sources on a receptor independently. The model is basically a linear model. Because properties that depend on other species are computed using background concentrations taken from a series of OPS concentration maps, one may call it a pseudo non-linear model.

The long-term OPS-LT model, which is outlined here, is a long-term Lagrangian transport and deposition model that describes relations between individual sources or source areas, and individual receptors by Gaussian plumes (see figure 21). The model is statistical in the sense that concentration and deposition values are calculated for a number of typical situations (classes) and the long-term value is obtained by summation of these values, weighted with their relative frequencies of occurrence.

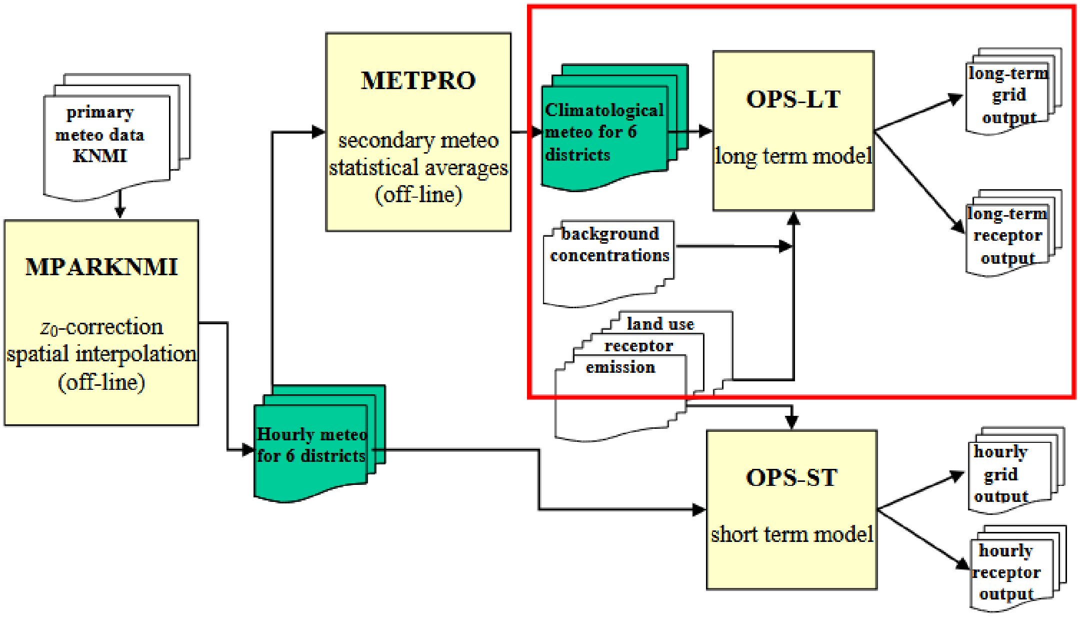


Figure 21: Schematic view of the long term and short term OPS models with its pre-processing steps by theprograms MPARKNMI and METPRO. Note that most users will only use the OPS-LT part in the red box (as used for CLINSH)

The area for which concentrations and depositions can be calculated is determined by the size of the area for which meteorological parameters are known. Since the standard climatological data set used for this model is based on observations from the Royal Netherlands Meteorological Institute (KNMI), the maximum size of the receptor area becomes, in effect, the Netherlands and adjoining regions. Receptor parameters that need to be specified are coordinates, roughness length and land use. The receptor height is fixed within the OPS model. In terms of the vertical dispersion, the receptor height is set to 0 m. In terms of the influence of dry deposition on the vertical concentration profile, the receptor height is 3.8 m, in other words, the measuring height of the Netherlands' air quality measuring network (LML).

The creation of background maps consists of three steps, of which step 1 and 2 are performed within this iterative procedure; the iteration stops if the grid averaged concentration differs less than 0.5%.
1. Computation Concentration maps are computed with the OPS model for the sample years 1984, 1994, 2005, 2012 and the year 2020, using detailed emission data.
2. Calibration Modelled concentrations (computed with a separate OPS-computation at receptor points) are compared with observations of the LML network and the maps are multiplied by the average ratio observed/modelled for each of the sample years.
3. Interpolation in time for each year (starting in 1980), trend factors relative to the sample years are determined from the observations. The concentration map for a specific year is then computed by scaling one of the sample year maps with this trend factor. The trend factor for the map of the future year is equal to 1 by definition.

For more information on the OPS model in English see https://www.rivm.nl/media/ops/OPS-model.pdf.

In the original report Description and validation of OPS-Pro 4.1, (van Jaarsveld, 2004)[25] various model validation exercises, have been presented. Since then, many more model intercomparison studies and validation exercises have been published:

[25] , RIVM report 500045001/2004 (vanJaarsveld, 2004)

1. A study on the influence of sea-salt particles on the exceedances of daily PM10 air quality standards in van Jaarsveld and Klimov (2011).
2. A comparison between modelled and measured wet deposition levels of ammonium, nitrate and sulphate over the period 1992-2008 in van der Swaluw et al. (2011).
3. An application of the OPS-model in modeling the spread of Q-fever bacteria in The Netherlands in van Leuken et al. (2016).
4. A comparison between the OPS-model, the grid model LOTOS-EUROS and a hybrid combination of both models for several components (i.e. gas, particles and deposition) in van der Swaluw et al. (2017).
5. An evaluation of emission and concentration trends of ammonia in The Netherlands in Wichink Kruit et al. (2017).
6. A model comparison between CHIMERE and OPS-ST for spatial patterns in ammonia in Azouz et al. (2019).
7. Evaluations of yearly produced large-scale maps of air pollution in the Netherlands in Hoogerbrugge et al. (2019).

Für weitere Informationen über das OPS-Modell in englischer Sprache siehe https://www.rivm.nl/media/ops/OPS-model.pdf.

3.5.2 Methods for calculating the emissions of transport in the Netherlands 2019

How the emissions from the different emissions sources used in the OPS model are derived can be found in the following report: https://www.pbl.nl/sites/default/files/downloads/4616-methods-for-calculating-the-emissions-of-ransport-in-nl.pdf

The sources that cause emissions of environmental pollutants can roughly be divided into stationary and mobile sources. Mobile sources include various means of transport such as passenger cars, heavy-duty trucks, inland waterway vessels and aircraft, as well as mobile machinery with combustion engines, such as agricultural tractors and forklifts. Inland navigation is defined as all motorized vessels that travel on the inland waterways in the Netherlands. Transport on the inland waterways comprises, among other things, professional freight transport, passenger transport and recreational craft. Different methodologies are used for calculating the emissions from freight shipping, passenger vessels and recreational craft. The methodologies are described in the report

The methodology for determining the emission factors for professional inland shipping is described in the EMS protocol for inland shipping (Hulskotte, 2018)[26][27]. The emission calculation is based on the energy consumption per vessel class, which is calculated from the travelled vessel kilometres. For 31 vessel classes, the power demand (kW) is calculated for the various inland waterway types and rivers in the Netherlands by means of a model described by Bolt (2003). In the EMS-protocol for inland shipping, a distinction is made between primary engines and auxiliary engines. For recreational craft, the emissions are calculated by multiplying the number of recreational vessels (allocated to open motor boats/cabin motor boats and open sailboats/cabin sailboats) with the average fuel consumption per boat type times the emission factor per substance, expressed in emission per engine type per quantity of fuel. The fuel consumption estimates of passenger boats and ferries have not been updated

[26] EMS-protocol Emissies door Binnenvaart: Verbrandingsmotoren Versie 4 15 december 2012
[27] Methods for calculating the emissions of transport in the Netherlands 2018, Task Force on Transportation of the Dutch Pollutant Release and Transfer Register

since 1994 and should be re-evaluated. Also, data concerning the number of recreational boats and their activity needs re-evaluation.

The emission scenario's from B3 need to be fitted into the OPS model using the system how the EMS data is fitted into OPS as well. .

3.5.3 Method to upload the data from the emission model (B3)in OPS

3.5.3.1 Sources used

Every year, RIVM (National Institute for Public Health and the Environment) makes maps that show the air pollution in the Netherlands. https://www.rivm.nl/bibliotheek/rapporten/680362001.pdf) This report presents the methods used for producing the maps. It maps the concentrations of a lot of substances, including nitrogen dioxide (NO2), ammonia, particulate matter and the quantity of nitrogen deposited on soil and plants (known as 'the nitrogen deposition'). In addition to its annual calculations, RIVM draws up forecasts for 2020, 2025 and 2030. These maps are uploaded into the OPS model Yearly. The emissions from Emissie Registratie (Pollutant Release and Transfer Register) form the base of these air pollution maps. For inland shipping the emissions are calculated according to the EMS protocol for inland shipping as described in 3.5.2. To calculate the effect of the different CLINSH scenario's we need to replace part of these emissions with the CLINSH emissions. The CLINSH emissions were delivered by B3 as Berthing Inland_emissions-DCMR 2020 baseline (s2020b/s2035b/s2035c) and Sailing Inland_emissions-DCMR 2020 baseline (s2020b/s2035b/s2035c). For the calculations we also received information on sailing routes and fairways by Rijkswaterstaat (Ministry for Infrastructure and Water Management).

3.5.3.2 Comparison CLINSH emission to the RIWM emissions

First of all a comparison was made between the CLINSH emissions (s2020b) and the RIVM (2019) emissions (used for Dutch modelling). The comparison was made on total emissions per km^2. For the Dutch modelling an effort was made to keep very close to the methodology that is used for the calculation of the national air quality calculations. The same model was used (OPS) and the same emission source data per 1x1 km^2 as well as their source parameters.

Differences leading to varying 1x1 km2 emission fluxes are mainly due to the following differences:

- CLINSH emissions have been determined on the basis of AIS data and individual vessels whereas RIVM data and emissions are categorized by ship types.
- CLINSH emissions distinguish between sailing and shipping emissions, RIVM ship type emissions do not.
- Through the use of AIS data the CLINSH emissions are geographically more accurate than RIVM emissions and no shipping emissions occur in 1x1 km^2grid cells without waterways.

The absolute differences are shown in the following charts (22/25). The data in the tables shows the effect within the municipal borders of Nijmegen and Rotterdam for emissions (g/s) and modelled immisions (µg/m^3).

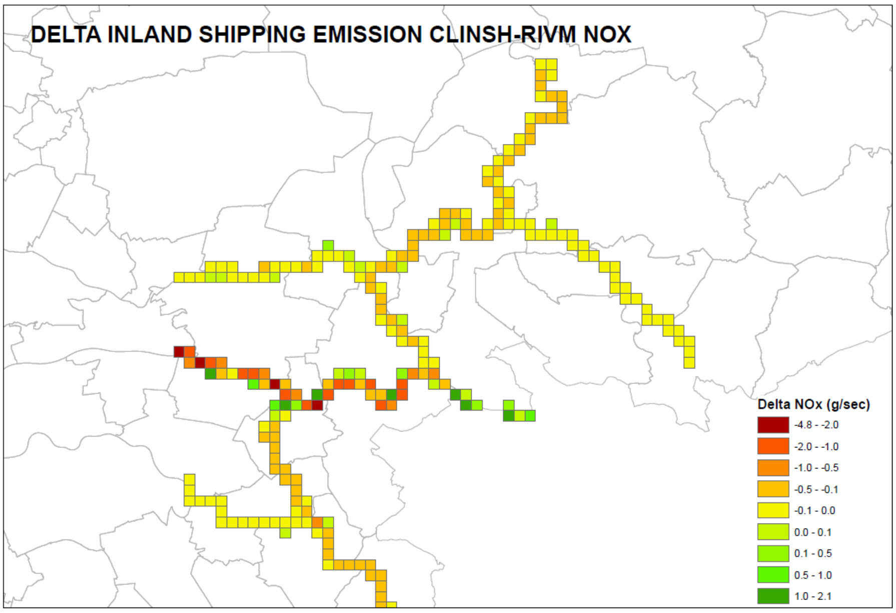


Figure 22: the Delta for NOx shipping emissions using Clinsh and RIVM emission factors (g/sec)Nijmegen

City	Component	RIVM	CLINSH	Delta
Nijmegen	NOx (g/sec)	17.37	7.60	-9.80

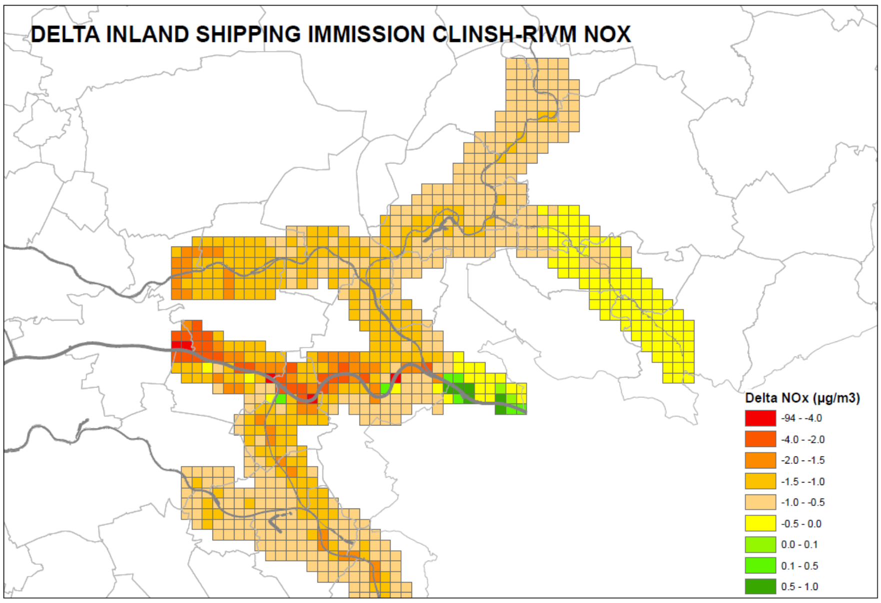


Figure 23: the Delta for NOx shipping emissions using Clinsh and RIVM emission factors (µg/m3) Nijmegen

City	Component	RIVM	CLINSH	Delta
Nijmegen	NOx (µg/m3)	2.41	0.92	-1.48

RIVM data around Nijmegen show more intense traffic on the river Waal and total RIVM emissions on this waterway are clearly higher than the CLINSH emissions. Also, a section of the river Rhine near Tolkamer (along the NL-DE border) is not entirely included in the RIVM emissions inventory domain and RIVM emissions in this area turn out to be lower than the CLINSH emissions.

De differences in immissions can be entirely explained by the observed differences in the emissions data. River Waal concentrations fort he RIVM model are clearly higher.

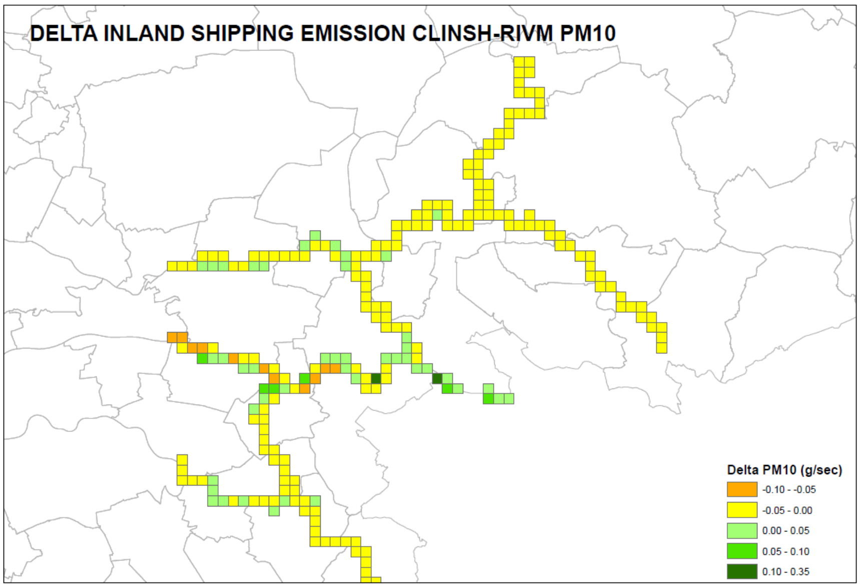


Figure 24: the Delta for PM10 shipping emissions using Clinsh and RIVM emission factors (g/sec) Nijmegen

City	Component	RIVM	CLINSH	Delta
Nijmegen	PM10 (g/sec)	0.60	0.44	-0.15

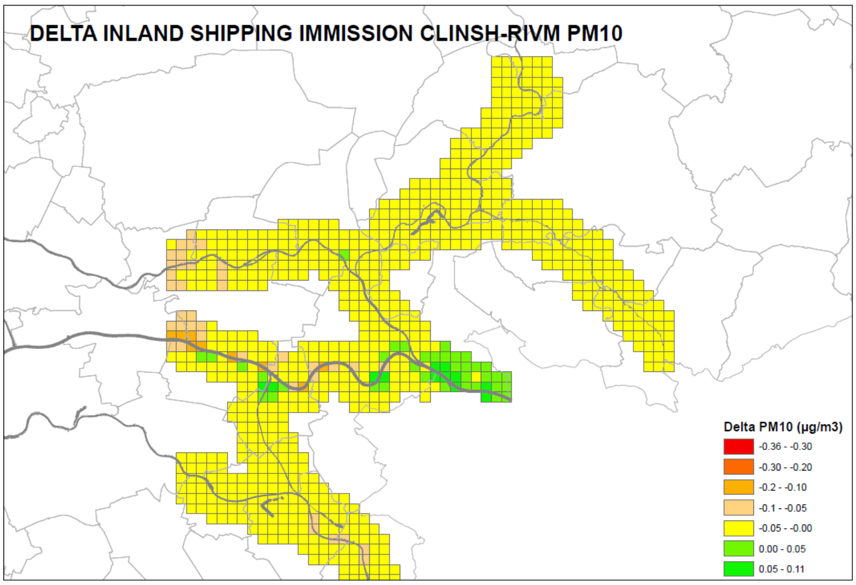


Figure 25: the Delta for NOx shipping emissions using Clinsh and RIVM emission factors (µg/m3)Nijmegen

City	Component	RIVM	CLINSH	Delta
Nijmegen	PM10 (µg/m3)	0.09	0.06	-0.03

A similar picture appears for PM_{10} emissions and immissions. The main differences between the CLINSH and RIVM models can be explained from differences in traffic intensity data that were used for the emissions source data.

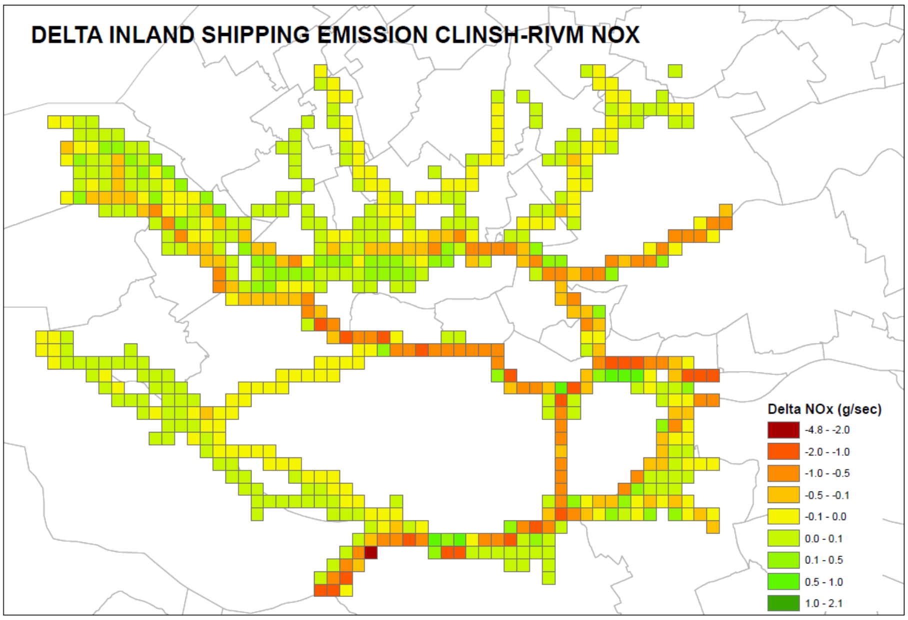


Figure 26: the Delta for NOx shipping emissions using Clinsh and RIVM emission factors (g/sec)Rotterdam

City	Component	RIVM	CLINSH	Delta
Rotterdam	NOx (g/sec)	53.34	37.13	-16.21

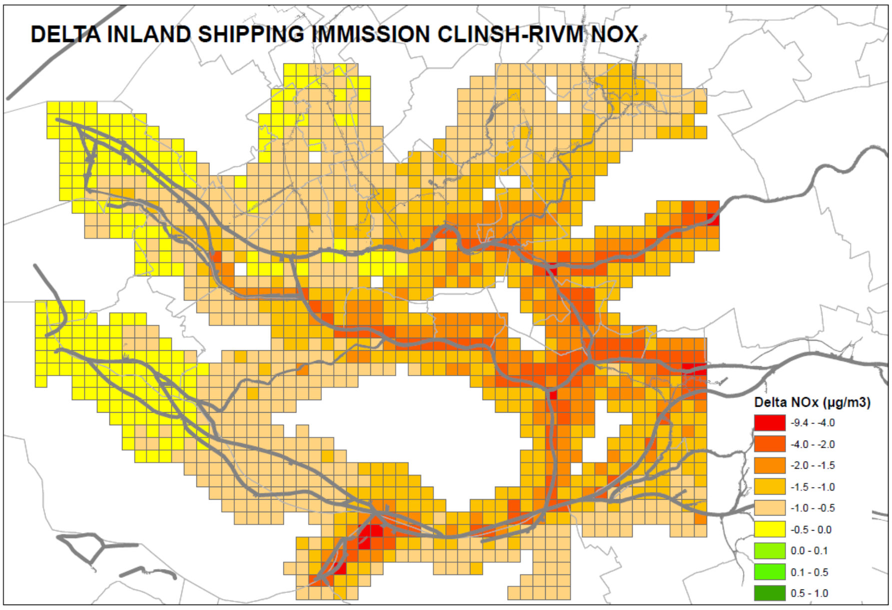


Figure 27: the Delta for NOx shipping emissions using Clinsh and RIVM emission factors (µg/m3) Rotterdam

City	Component	RIVM	CLINSH	Delta
Rotterdam	NOx (µg/m3)	2.11	1.14	-0.97

In Rotterdam too the RIVM NOx emissions are higher. The main differences occur at the rivers Oude Maas, Dordtse Kil and Hollands Diep. These waterways are typically used by the larger vessels for international traffic which can be seen from the RIVM ship categories data. Differences between the two models may therefore be due to different traffic intensities, but possibly also because of the attributed emission factors for the vessel types.

In the Rotterdam area positive and negative values may occur in neighbouring 1x1 km^2 grid cells, which can be explained from the different ways in which the emissions were projected and allotted spatially. Here too, differences in NOx immisions are quite similar to the picture for emissions and the differences between the model results can be contributed entirely to the observed differences in emissions data.

In the case of PM_{10} the results for Rotterdam show the opposite of the NOx results, as the RIVM PM_{10} emissions are lower than in the case of the CLINSH model. The Rotterdam result is also different form the Nijmegen area. This indicates that these differences are not caused by varying traffic intensities among the models, but by the application of differing emission factors. This in turn may depend on differing ship types in the models. Higher CLINSH emissions are especially seen in the port areas outside the main waterway routes.

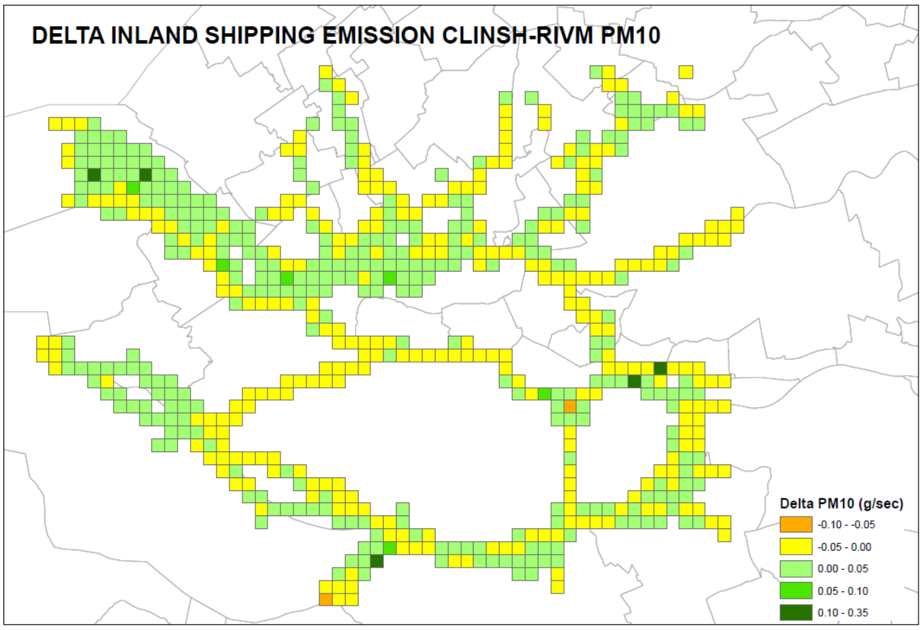


Figure 28: the Delta for PM10 shipping emissions using Clinsh and RIVM emission factors (g/sec) Rotterdam

City	Component	RIVM	CLINSH	Delta
Rotterdam	PM10 (g/sec)	1.84	3.17	1.33

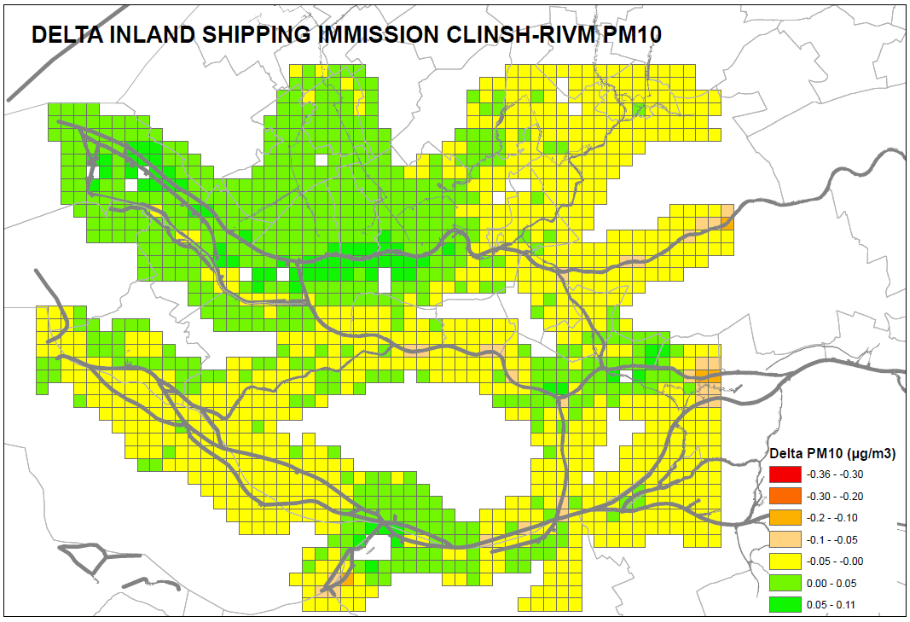


Figure 29: the Delta for NOx shipping emissions using Clinsh and RIVM emission factors (µg/m3)Rotterdam

City	Component	RIVM	CLINSH	Delta
Rotterdam	PM10 (µg/m3)	0.08	0.10	0.02

In conclusion, the use of AIS data results in a better spatial allocation of the emissions data than in the case of the RIVM inventory. Allocating RIVM emissions to the actual waterways and harbours (rather than 1x1 km^2 grid cells) will lead to better immissions results. Also, applying a distinction between sailing vessels and berthing vessels will help to improve emissions data. The comparison also highlights differences in the applied emission factors of ships and of ship types.

3.5.3.3 Preparing the model and the emission scenario's to be uploaded

For IWT in the Netherlands 5 categories of ships are used in the GCN data.

- 3861 Internationaal Vrachtvervoer (freight)
- 3862 Internationaal Vrachtvervoer-Duwvaart (freight pushbarges)
- 3863 Nationaal Vrachtvervoer (freight)
- 3864 Nationaal Vrachtvervoer-Duwvaart (freight pushbarges)
- 3865 Passagiersboten (passenger)

The ratio of these 5 categories was established per km^2 for the situation in 2020 and 2030 (RIVM has no scenario for 2035). The CLINSH scenarios delivered by B3 were then distributed over these categories.

Table 10: The different ship categories (3861-3865) have different emission characteristics.

Categorie	hc (MW)	h (m)	s (m)
3861 Int.Vrachtvervoer	0.4	2.8	1.4
3862 Int.Duwvaart	0.9	2.8	1.4
3863 Nat.Vrachtvervoer	0.3	3.0	1.5
3864 Nat.Duwvaart	0.8	2.8	1.4
3865 Passagiersboten	0.9	12	6

hc(MW) *emission heat capacity (MW)*
h(m) *height of source (m)*
s(m) *sigma of source height variation (m)*

The emissions of the IWT of different scenario's were delivered per km^2. The emissions are known to take place in the waterways or harbours and can therefore be relocated accurately. a 100x100 m^2 grid was applied to relocate these 1x1 km^2 emissions. This was done for both sailing (waterways or harbours) and berthing emissions (harbours or official berthing places). See figures 30 and 31

In de B3 files containing the Berthing -emissions for the scenarios, emissions were detected in km^2 grids outside of harbours or official berthing places. These emission were allocated to ships that stayed in the same place for longer than 2 hours and distributed to the 100x100 m^2 grid cells at the edges of the fairways.

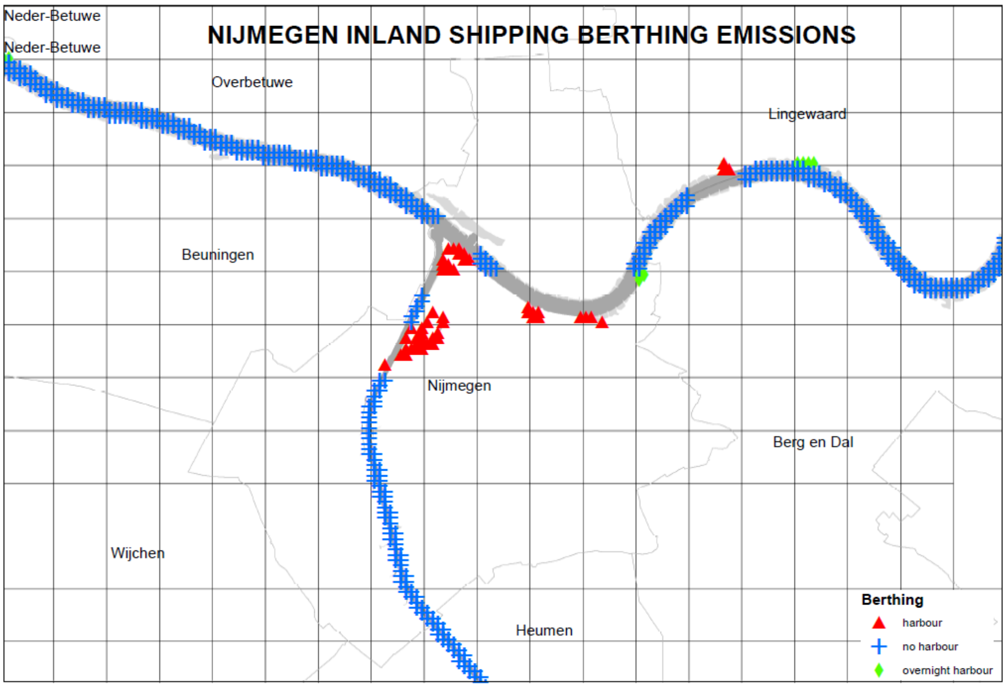


Figure 30: Nijmegen inland shippng bething locations

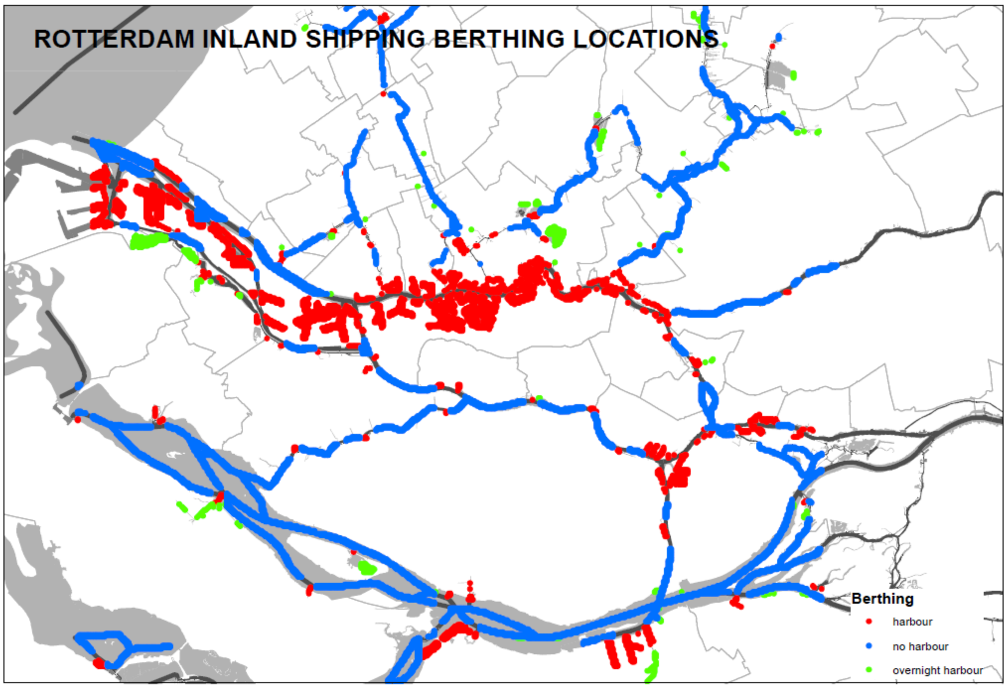


Figure 31:Rotterdam inland shipping berthing locations

The RIVM source data makes no distinction between sailing and berthing emission so we could not determine where what ships were at berth. We decided to award the emissions of all berthing ships to the category 3861 (Internationaal Vrachtvervoer (freight)).

The sailing and berthing emission files were then combined into one source file while keeping the distinction between sailing and berthing.

Table 11: The following emission files were made

Name	**Component**	**Location**	**year**
NOX_Nijmegen_2020 (s2020b)	NOX	Nijmegen	2020
NOX_Nijmegen_2035 (s2035b)	NOX	Nijmegen	2035
NOX_Nijmegen_CLINSH (s2035c)	NOX	Nijmegen	2035
PM10_Nijmegen_2020 (s2020b)	PM10	Nijmegen	2020
PM10_Nijmegen_2035 (s2035b)	PM10	Nijmegen	2035
PM10_Nijmegen_CLINSH (s2035c)	PM10	Nijmegen	2035
NOX_Rotterdam_2020 (s2020b)	NOX	Rotterdam	2020
NOX_Rotterdam_2035 (s2035b)	NOX	Rotterdam	2035
NOX_Rotterdam_CLINSH (s2035c)	NOX	Rotterdam	2035
PM10_Rotterdam_2020 (s2020b)	PM10	Rotterdam	2020
PM10_Rotterdam_2035 (s2035b)	PM10	Rotterdam	2035
PM10_Rotterdam_CLINSH (s2035c)	PM10	Rotterdam	2035

For Nijmegen there are 1.960 emission points and for Rotterdam: 65.821 emission points

3.5.3.4 Receptor files

For Rotterdam and Nijmegen receptor files were made, with grid cells of 100x100 m^2. It wasn't technically possible to calculate the whole area where emissions were delivered by B3, so in Nijmegen receptors were made up to 2 km from the fairways or harbours In Rotterdam receptors were made till 1 km from the fairways or harbours (see figure 32)

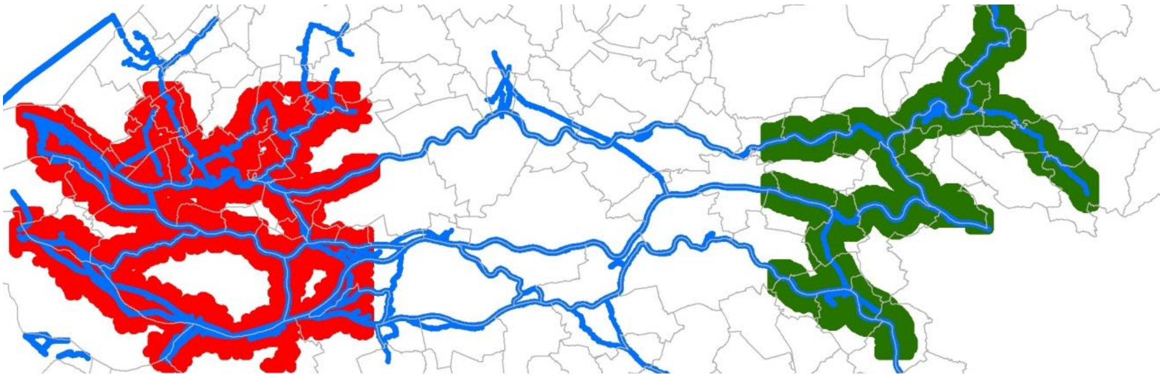


Figure 32: receptor point for Rotterdam (red) and Nijmegen (green)

3.5.4 Modelling the Air Quality in Nijmegen and Rotterdam

With the generated emission files and receptor files OPS-Pro was executed using 2019 meteorology for the s2020 baseline case and a 10-years meteorology for the 2035 scenarios, giving the following results.

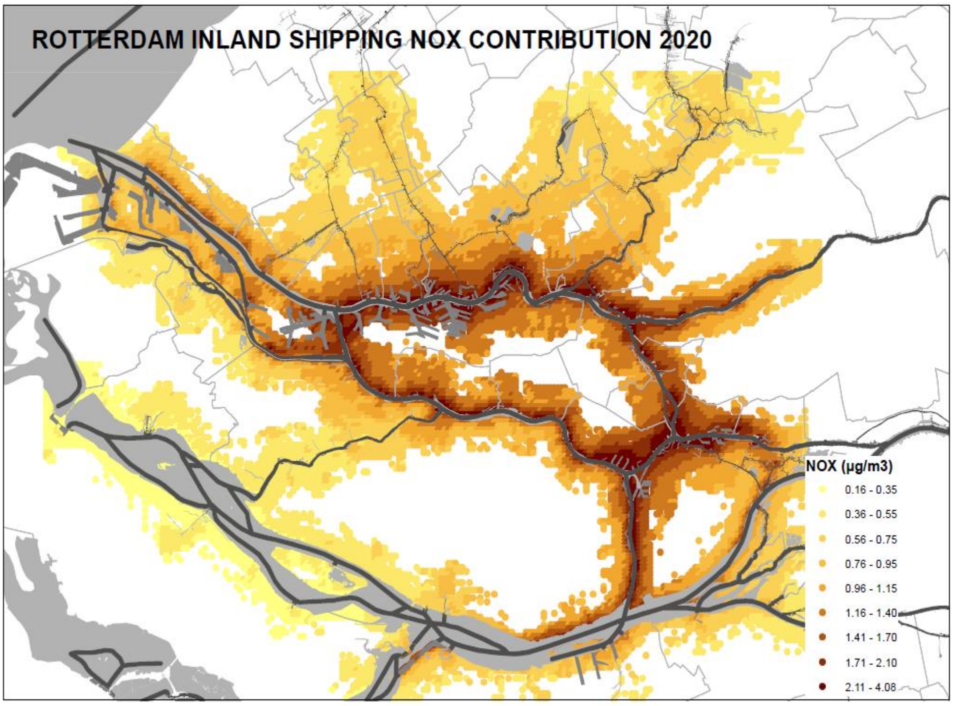


Figure 33: CLINSH baseline scenario for NOx for the year 2020.

City	Component	Min	Max	Average
Rotterdam	NOx	0.2	3.0	1.2

Figure 33 shows the NO_x concentrations in the Baseline scenario for the year 2020. Results are in NOx and not NO_2 because the model is generally used for policy advice and not a chemical transport model. NO_x concentrations can be converted to NO_2 concentrations in cases where there is a lot of information about the different emission sources, but the modelling of NO_x concentrations is more accurate thus in the Netherlands the NO_x concentrations are often used to evaluate different policy measures. Roughly, about 50% of the NO_x concentrations is NO_2 in the Rotterdam area. In the Baseline scenario in 2020, inland shipping contributes between 0.2 to 3.0 µg/m³ NO_x with an average of 1.2 µg/m³ NO_x.

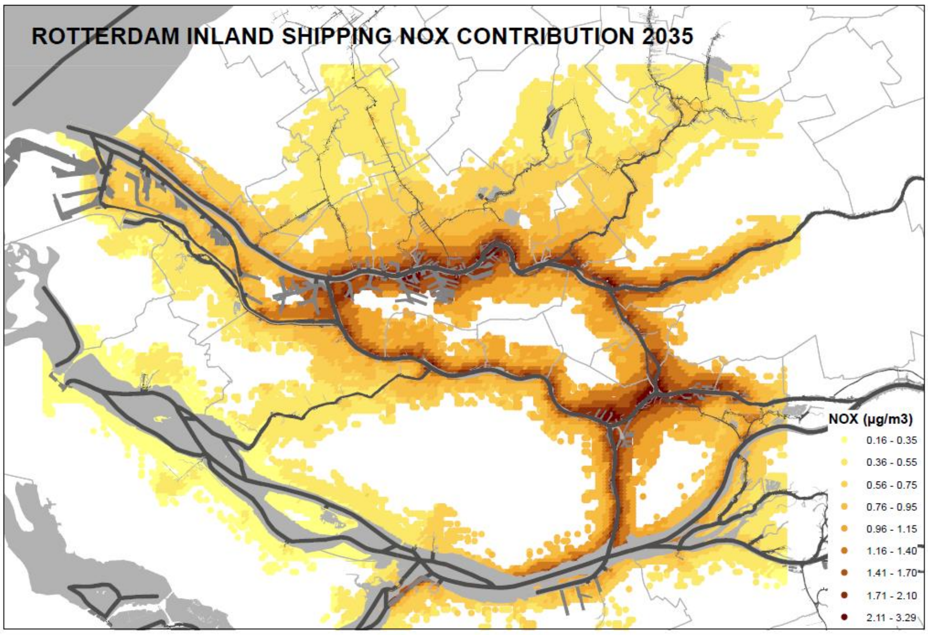


Figure 34: CLINSH baseline scenario for NOx for the year 2035

City	Component	Min	Max	Average
Rotterdam	NOx	0.2	2.6	1.0

Figure 34 shows the contribution of inland shipping to the NOx concentrations in the Baseline scenario in 2035. The contribution from IWT in the Rotterdam region varies between 0.2 and 2.6 µg/m³ with an average of 1 µg/m³. The contribution of the shipping is only slightly lower than in 2020.

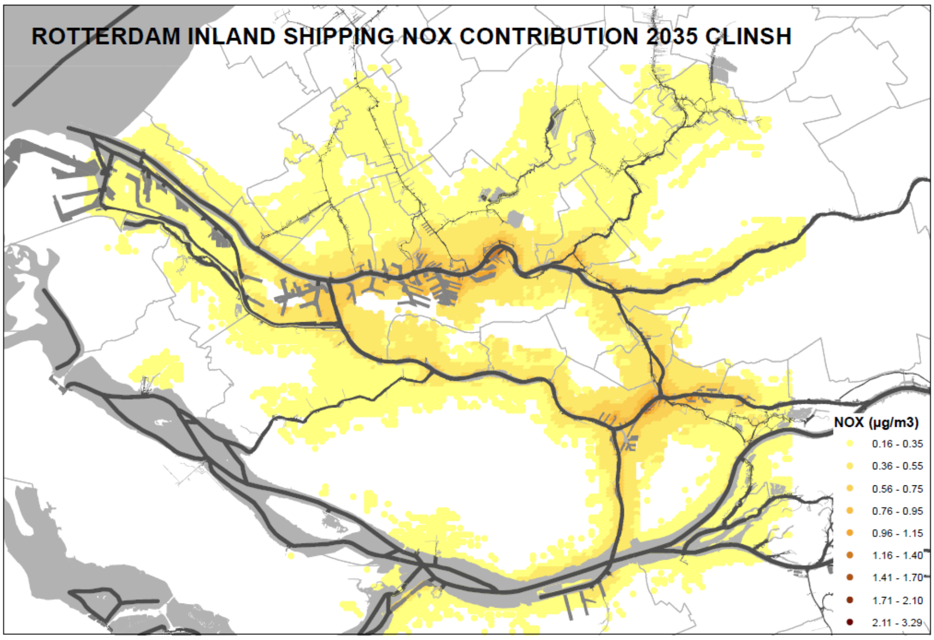


Figure 35: CLINSH scenario for NOx for the year 2035

City	Component	Min	Max	Average
Rotterdam	NOx	0.1	1.3	0.4

Finally, figure 35 shows the contribution of inland shipping to the NO_x concentrations in the CLINSH scenario in 2035. The contribution from IWT to the NO_x concentrations in Rotterdam is significantly lower in the CLINSH scenario. The contribution varies between 0.1 and 1.3 µg/m³ with an average of 0.4 µg/m³.

It is now possible to calculate the maximum reduction potential of the CLINSH scenario. figure 29 shows the difference between the Baseline and the CLINSH scenario, in other words the "CLINSH effect". The reduction potential varies between 0.1 and 2.1 µg/m³. The average impact drops from 1 µg/m³ in the baseline scenario to 0.4 µg/m³ in the CLINSH scenario. In Rotterdam, close to the inland harbours where the houses are close to the harbour, a reduction potential between 0.13 µg/m³ to 1.5 µg/m³ can be achieved. No local air quality measure has been able to accomplish such a strong effect so far.

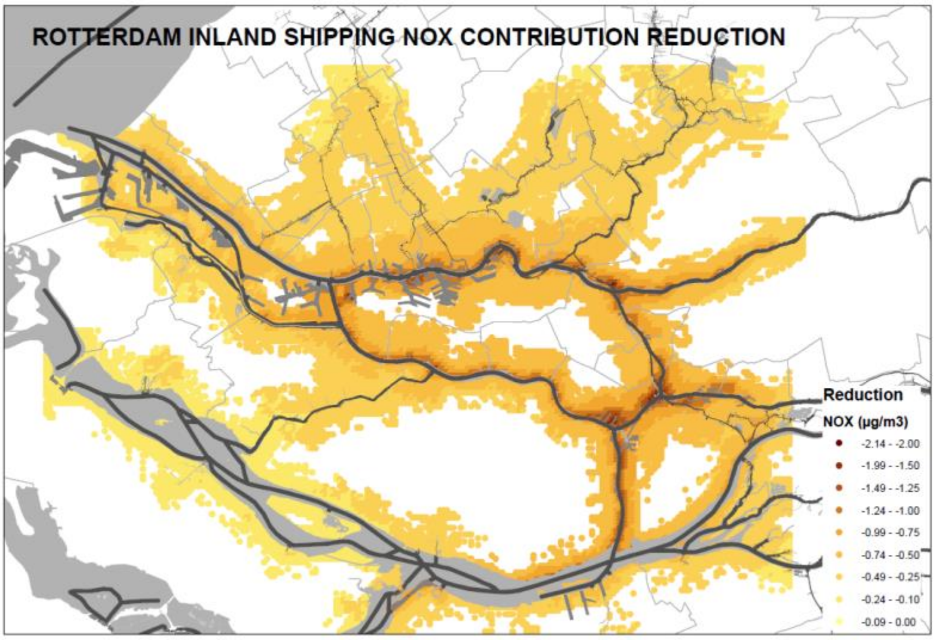


Figure 36: the maximum reduction potential of the CLINSH scenario

Scenario	Max. contribution µg/m³	Average contribution µg/m³	Reduction vs. average Baseline 2020
Baseline 2020	3.0	1.2	-
Baseline 2035	2.6	1.0	16%
CLINSH 2035	1.3	0.4	66%

Table 12 shows the amount of population that benefits from the CLINSH effect in Rotterdam. For over 150,000 inhabitants, the NO_x concentration decreases by 0.13 to 0.5 µg/m³. For over 27,000 inhabitant the NO_x concentration decreases by 1.25 to 1,50 µg/m³. Using the general rule of NO_x/NO_2 conversion for the Rotterdam area, the NO_2 concentrations decrease with 0.62 to 0.75 µg/m³ for these 27,000 inhabitants as a result of the realisation of the CLINSH scenario. The total population in the region is around 1.2 million people.

Table 12 – The effect of NOx reductions in the CLINSH scenario on the population of Rotterdam

Decrease of NOx contribution µg/m³	Inhabitants	Portion of Rotterdam population
-0.50 - -0.13	154,096	26%
-0.75 - -0.50	322,046	54%
-1.00 - -0.75	91,481	15%
-1.25 - -1.50	27,225	5%

The same calculations as for NOx were made for PM10 as well. With the generated emission files and receptor files OPS-Pro was executed using 2019 meteorology for the s2020 baseline case and a 10-years meteorology for the 2035 scenarios, giving the following results.

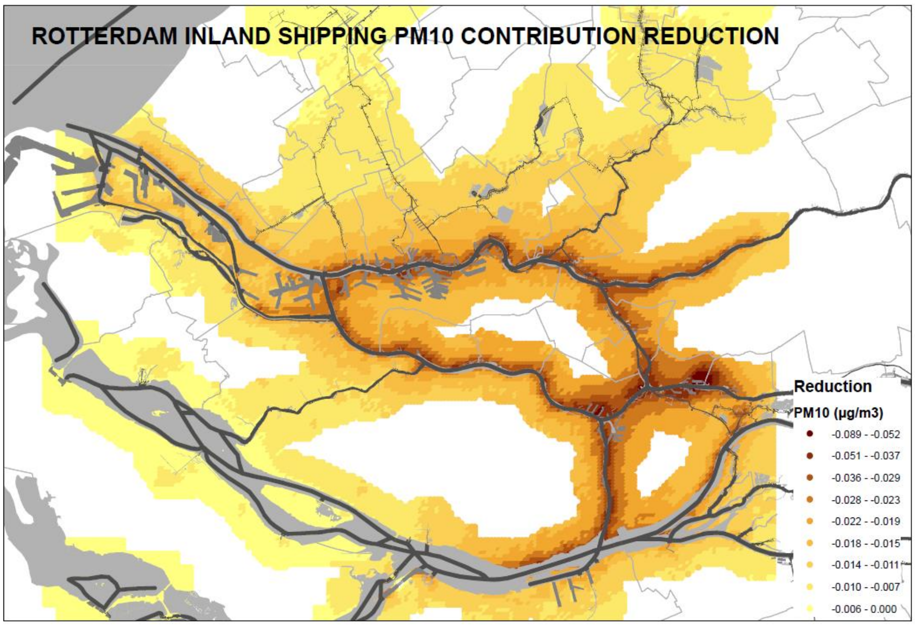


Figure 37: the maximum reduction potential of the CLINSH scenario for PM10 in Rotterdam

Scenario	Max. contribution µg/m³	Average contribution µg/m³	Reduction vs. average Baseline 2020
Baseline 2020	0,3	0,1	
Baseline 2035	0,11	0,02	
CLINSH 2035	0,08	0	100

It is now possible to calculate the maximum reduction potential of the CLINSH scenario. figure 37 shows the difference between the Baseline and the CLINSH scenario, in other words the “CLINSH effect”. The reduction potential maxes at 0.03 µg/m³. The average impact drops from 0.02 µg/m³ in the baseline scenario to 0 µg/m³ in the CLINSH scenario. The Pm10 contribution of the inland shipping in Rotterdam is very low.

The calculations that were made for Rotterdam were made for Nijmegen as well.

Figure 38) CLINSH baseline scenario for NOx for the year 2020.

City	Component	Min	Max	Average
Nijmegen	NOx	0,2	5,7	1

Figure 38 shows the contribution of inland shipping to the NOx concentrations in the Baseline scenario in 2035. The contribution from IWT in the Nijmegen region varies between 0,2 and 5,7 µg/m³ with an average of 1 µg/m³. The contribution of the shipping is only slightly lower than in 2020.
Figure 39 shows the contribution of inland shipping to the NOx concentrations in the Baseline scenario in 2035. The contribution from IWT in the Nijmegen region varies between 0,2 and 5 µg/m³ with an average of 0,9 µg/m³. The contribution of the shipping is only slightly lower than in 2020.

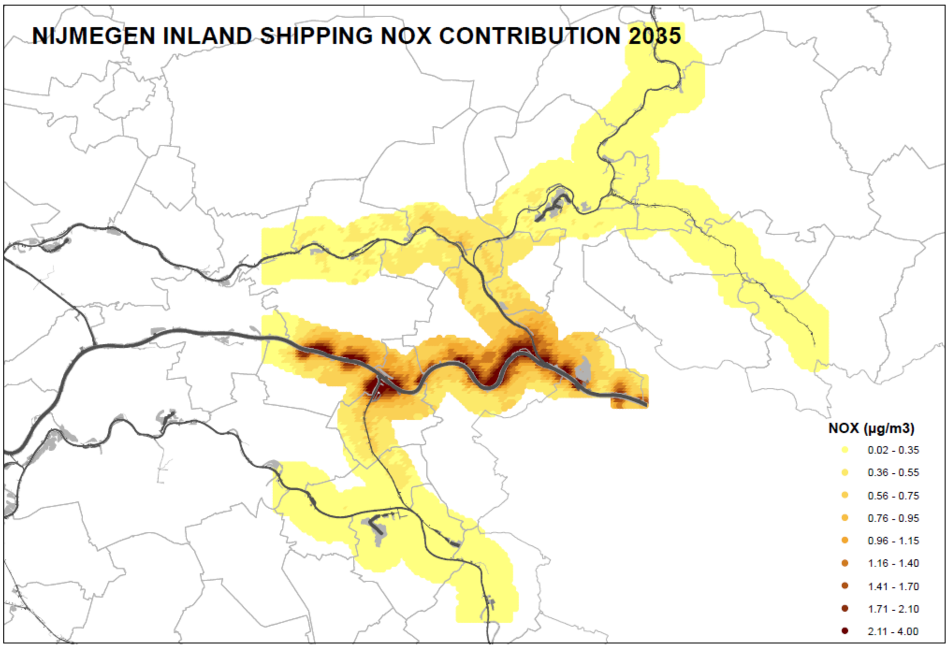


Figure 39:) CLINSH baseline scenario for NOx for the year 2035

City	Component	Min	Max	Average
Nijmegen	NOx	0,2	5	0,9

Finally, figure 40 shows the contribution of inland shipping to the NO_x concentrations in the CLINSH scenario in 2035. The contribution from IWT to the NO_x concentrations in Nijmegen is significantly lower in the CLINSH scenario. The contribution varies between 0,1 and 1,5 µg/m³ with an average of 0,3µg/m³.

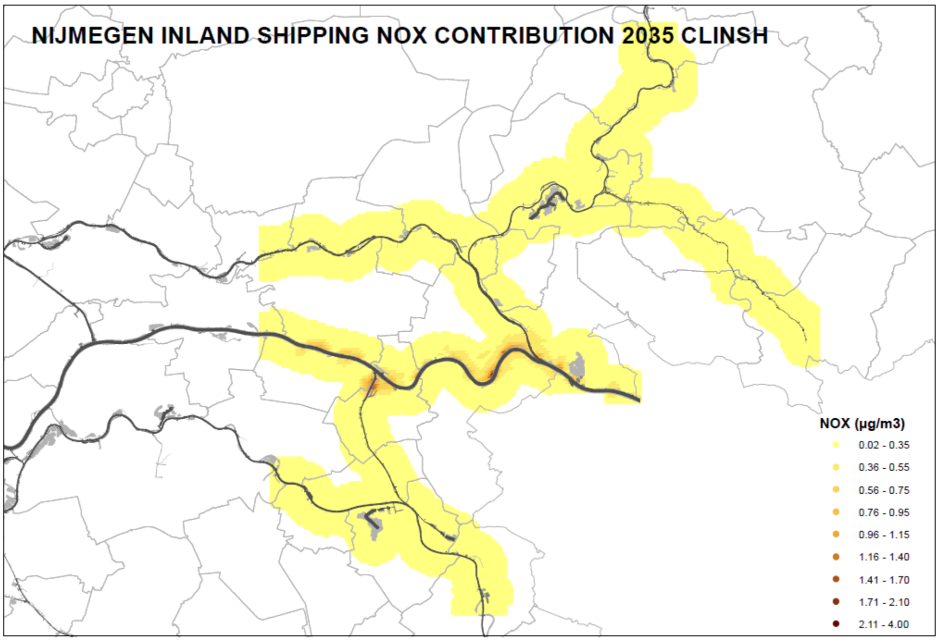


Figure 40: CLINSH scenario for NOx for the year 2035

City	Component	Min	Max	Average
Nijmegen	NOx	0,1	1,5	0,3

It is now possible to calculate the maximum reduction potential of the CLINSH scenario. figure 41 shows the difference between the Baseline and the CLINSH scenario, in other words the "CLINSH effect”. The reduction potential has a maximum of 4,5 µg/m³. The average impact drops from 0.9 µg/m³ in the baseline scenario to 0.3 µg/m³ in the CLINSH scenario

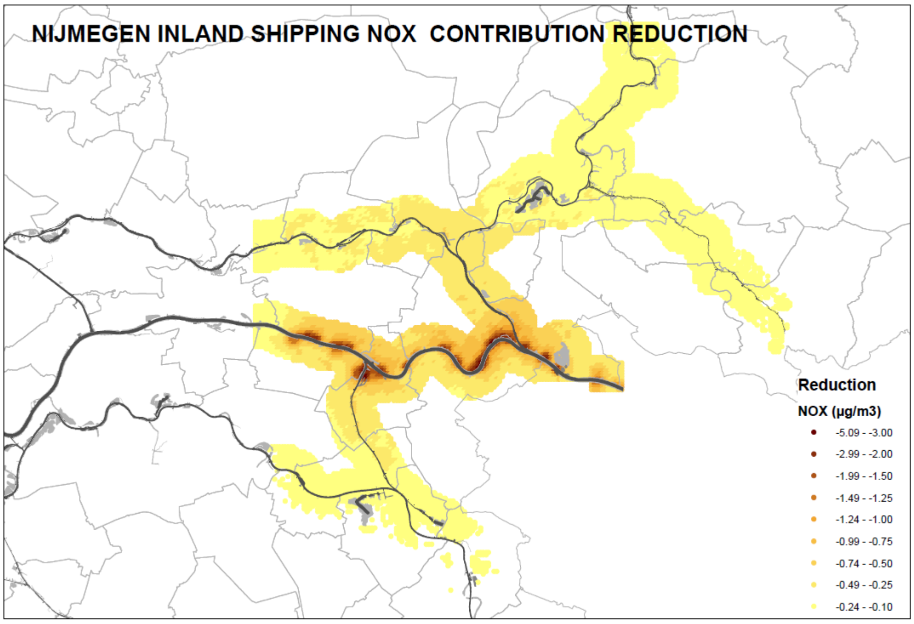


Figure 41: the maximum reduction potential of NOX for the CLINSH scenario

2035 NOx in µg/m³		
scenario	Max.	Average
Base	5	0.9
Clinsh	1.5	0.3

The same calculations as for NOx were made for PM10 as well. With the generated emission files and receptor files OPS-Pro was executed using 2019 meteorology for the s2020 baseline case and a 10-years meteorology for the 2035 scenarios, giving the following results.

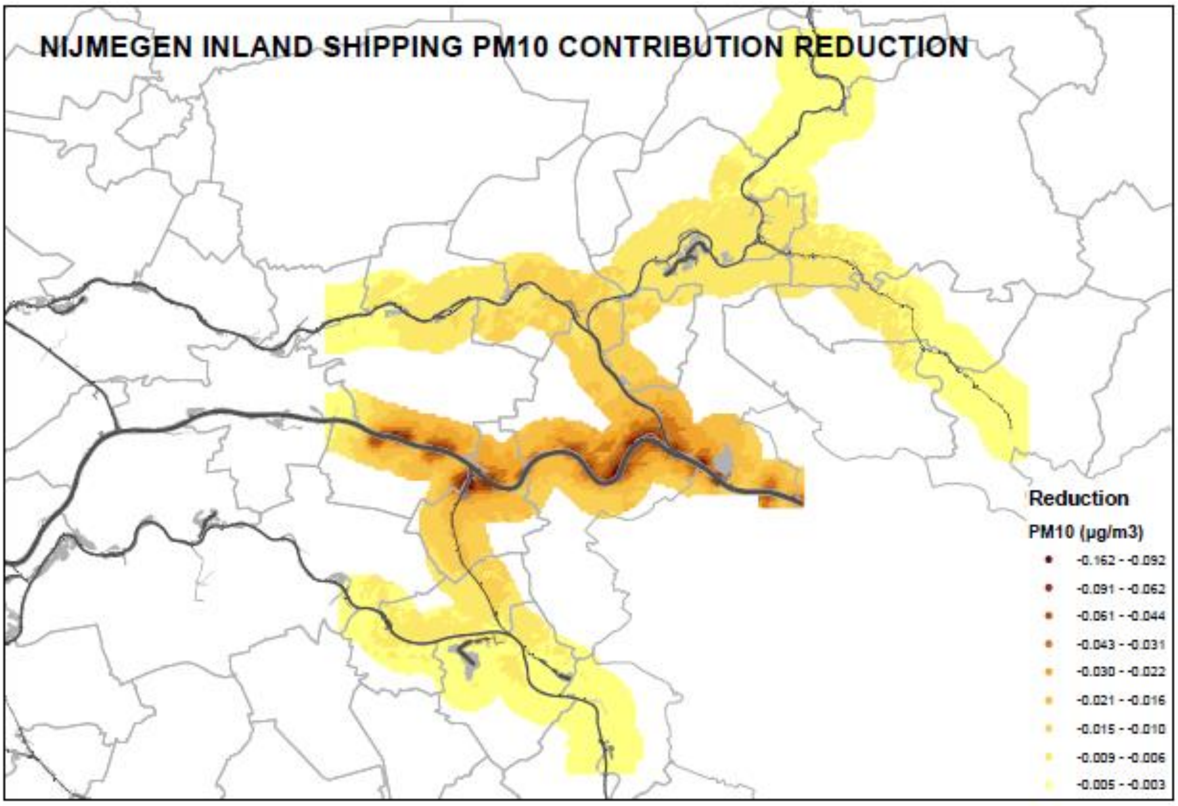


Figure 42: the maximum reduction potential of PM for the CLINSH scenario

Scenario	Max. contribution µg/m³	Average contribution µg/m³
Baseline 2020	0,2	0,04
Baseline 2035	0,14	0,03
CLINSH 2035	0,02	0

4 Conclusions and lessons learned

4.1 conclusions

- The intensive monitoring of air quality in the ports of Neuss and Duisburg showed that the concentrations of NO_2 at the measuring points on the Rhine and in the port areas were significantly lower than previously assumed.
- In the area of the German-Dutch border near Bimmen-Lobith, the effect of NO_X emissions from 110,000 passing inland vessels per year on air quality could be determined directly. On the left bank of the Rhine (windward side), the ship emissions led to increases in the annual mean NO_2 concentrations up to 2 µg/m³ and on the right bank (leeward side) up to 4.6 µg/m³. The annual mean NO_2 concentrations on the leeward bank in Lobith fell from 21 µg/m³ in 2017 to 18.1 µg/m³ in 2020.
- With the automatic measuring stations, the NO_X emission peaks (measuring frequency 5 sec) of passing ships can be identified and quantified. The assignment to the ships is done by recording the AIS data.
- With more than 8,000 quantifications from real measurement results, it was possible to compile a catalogue of onshore emission factors for inland vessels on the Lower Rhine,

classified according to vessel size, direction of travel (upstream/downstream) and speed over ground. With this catalogue and the recording of real ship traffic, a new method for determining the emissions of moving ships was developed and applied for the study area Neuss-Duisburg within the framework of CLINSH. The emission data are now no longer based on estimates of theoretical diesel consumption from performance/emission curves but on real measured onshore data.

- With the acquisition and evaluation of AIS data, it is possible by using a suitable evaluation programme, to record the real ship traffic with regard to ship type, ship size, direction of travel and speed over ground. However the range of AIS transmitters and receivers is limited. The range of AIS transmitters depends on the transmitter strength and the antenna height. Large container ships with the bridge raised have a much greater range than ships with a lower antenna height.
- The application of the presented air quality modeling system EPISODE-CityChem in the urban domains Rotterdam, Antwerp, Nijmegen and Western Rhine-Ruhr area led to the identification of inland shipping impacts in a scenario representing the current conditions, as well as two future scenarios following the outcomes of the CLINSH project
- The presented modeling system is intended as a tool that can be applied to any region in Europe using the same publicly available input data for meteorology, boundary conditions and emissions. This allows for a direct comparison between different areas based on the same assumptions and datasets. Therefore, the presented approach is considered to be a consistent approach.
- When comparing the reduction potentials for inland shipping emissions, with reduction potentials for the simulated concentrations, it becomes evident, that there are no linear connections. This is due to consideration of atmospheric and pollutant chemistry in the EPISODE-CityChem model: secondary particle formation, deposition processes and photochemistry are the main drivers for PM_{10} and NO_2 formation and degradation in the atmosphere. Thus, it is clearly necessary to apply air quality modeling systems such as EPISODE-CityChem to take into account all relevant processes that can influence air quality levels.

4.2 lessons learned

- Due to traffic density, river morphology, flow conditions, current quays as well as harbor and canal entrances, the speed of the moving ships is not homogeneous and changes frequently. Since different pollutant quantities are also emitted at different speeds, the calculation of emissions and the determination of emission density for modelling should be carried out in sections, e.g. per river kilometer.
- On the Lower Rhine, AIS signals can be received within a radius of about 10 river kilometers. At further distance the number of ships detected by the station decreases until only individual, mostly larger container ships are detected.
- Due to equipment failure and transmission disturbances, data gaps can occur temporarily, covering several hours up to several days or even longer periods. These gaps must be filled by a suitable method if the annual number of ships is to be determined.
- None of the CLINSH partners had an applicable method for a realistic detailed determination of the emissions of the berthed ships. Therefore, a suitable method was developed by LANUV *see guidebook XX*.
- The spatial distribution of the berthed ships in the harbor basins can be recorded by evaluating the AIS signals. The characteristics of the emissions for the cargo ships correspond to a line source, those of the emissions of the tankers through the fixed unloading and loading facilities

to those of a point source. The attempt to determine the number of berthed ships by evaluating the AIS data resulted in implausibly high numbers. There is still a need for further development of the detection method via the AIS data in future to use this data in modelling.

-
- The calculations of the emissions of the moored ships in the ports of Neuss and Duisburg resulted in significantly lower emission amounts of NO_X and PM_{10} than expected at the beginning of the project.
- The use of AIS signals to determine the number of ships in port must be further developed in order to determine realistic ship numbers. A comparison with the data of the port operators is necessary.
- such a consistent modeling chain also implies some shortcomings. Due to the application of harmonized European datasets, city-specific emission inventories are not applied in the modeling chain. Therefore, the accuracy of modelled values compared to observed values might be lower. This needs to be taken into account, in the choice of this modeling chain for a suitable application. While it is possible to achieve comparable qualitative results, such as the contribution of a specific emission sector in different cities or regions, the presented modeling chain and its results in this report are not sufficient for air quality reporting. To suffice for air quality reporting the air quality simulations performed within the CLINSH project would need in-depth analyses and city-specific inventories and parametrization, which is generally possible but out of the scope of this project.
- there are some technical limitations, which come with the choice of an Eulerian grid Chemistry Transport model. The mean contributions of inland shipping as given in the tables in Figures 5, 6, 7 and 8 seem to be very low. But in the interpretation of these means it has to be taken into account that these means represent a mean of all grid cells of the 100m receptor raster in each domain and not only in the proximity or the area of influence of inland shipping activities. Thus, also areas with very low or non-existent contributions of shipping are taken into account in the calculation of the mean values. The mean concentrations arising from inland shipping are considerably higher in the proximity of the source.
- Another important aspect that needs to be considered in the result interpretation is the grid cell size (resolution). Inland shipping emissions are treated as area sources with a size of $1km^2$ in each modeling domain. Therefore, it is likely to happen, that high emissions at/over the shipping lanes or port areas become diluted and thus, the resulting concentrations calculated at the 100m receptor raster are relatively low. Such dilution effects, which are an inherent part of Eulerian grid chemistry transport models can be avoided with e.g. Lagrangian or Gaussian plume modeling approaches (e.g. the OPS model), which allow for much higher resolutions but mostly lack the chemical transformation of pollutants.

5 Literature

1. *“Harbour Monitoring Part A: Air quality on the Rhine and in the inland ports of Duisburg and Neuss/Düsseldorf. Immission-side effect of emissions from shipping and port operations on nitrogen oxide pollution" (already published)*
2. *"Harbour Monitoring Part B: Determination of NO_X and particulate matter emissions from inland vessels at berth" (already published)*
3. *"Harbour Monitoring Part C: Emission inventories for the ports of Duisburg and Neuss/Düsseldorf"*
4. *"Harbour Monitoring Part D: Analysis of shipping traffic on the Rhine for the years 2018-2020”*
5. *“Harbour monitoring Part E: Determination of NO_X emission rates of passing vessels from onshore measurements, comparison to onboard observations and application for emission calculations”*
6. *"Harbour Monitoring Part F: Root Cause Analyses for Air Quality Measurement Results in the Inland Ports of Neuss and Duisburg)”*

6 Annex I: Evaluation and results for monthly EPISODE-CityChem results January and July 2019 in Rotterdam, Antwerp, Nijmegen and Western Rhine-Ruhr area

Table 12: Evaluation statistic of hourly simulated vs. hourly measured values of NO_2 at all available stations.

area	type	month	n	FAC2	MB	NMB	RMSE	r	IOA
Rotterdam									
n.a.	industry	January	2229	0.59	-8.29	-0.28	19.68	0.49	0.53
n.a.	industry	July	2193	0.54	-3.00	-0.15	18.41	0.36	0.50
rural	background	January	743	0.79	-4.74	-0.21	11.86	0.71	0.65
rural	background	July	739	0.69	-0.28	-0.02	9.22	0.51	0.46
suburban	background	January	718	0.69	-12.19	-0.39	19.28	0.74	0.62
suburban	background	July	741	0.80	1.12	0.07	10.70	0.63	0.64
urban	backgorund	January	3694	0.83	-5.42	-0.18	14.66	0.74	0.69
urban	backgorund	July	3691	0.66	5.94	0.34	15.21	0.56	0.46
urban	traffic	January	3719	0.74	-8.58	-0.22	18.93	0.67	0.60
urban	traffic	July	4454	0.70	1.87	0.07	18.07	0.52	0.47
Nijmegen									
urban	background	January	731	0.85	-7.88	-0.29	12.51	0.76	0.62
urban	background	July	721	0.77	3.14	0.23	9.61	0.48	0.37
urban	traffic	January	695	0.90	-2.09	-0.06	12.93	0.71	0.63
urban	traffic	July	738	0.79	5.25	0.20	16.83	0.39	0.32
Antwerp									
n.a.	industrial	January	5815	0.80	-1.38	-0.04	0.38	0.60	0.58
n.a.	industrial	July	6363	0.62	8.52	0.41	0.70	0.50	0.35
suburban	background	January	2770	0.79	-0.78	-0.03	0.39	0.65	0.63
suburban	background	July	2600	0.52	8.89	0.63	0.92	0.41	0.20
urban	background	January	1310	0.82	-5.39	-0.14	0.35	0.55	0.53
urban	background	July	1432	0.70	8.38	0.41	0.62	0.51	0.37
urban	traffic	January	1420	0.72	-12.26	-0.28	0.38	0.63	0.47
urban	traffic	July	1442	0.68	-1.35	-0.05	0.49	0.38	0.45
Western Rhine-Ruhr area									
n.a.	industry	January	2484	0.67	-0.52	-0.02	21.58	0.18	0.32
n.a.	industry	July	2213	0.58	9.48	0.37	25.08	0.17	0.08
suburban	background	January	2505	0.55	-11.31	-0.36	20.48	0.31	0.37
suburban	background	July	2122	0.51	-5.49	-0.22	20.22	0.03	0.26
urban	backgorund	January	3634	0.68	-4.61	-0.14	18.52	0.36	0.43
urban	backgorund	July	3032	0.61	2.60	0.10	21.49	0.17	0.28
urban	traffic	January	5586	0.60	-17.29	-0.40	23.53	0.58	0.38
urban	traffic	July	5677	0.67	-10.25	-0.26	22.84	0.33	0.40

Table 2: Evaluation statistic of hourly simulated vs. hourly measured values of PM_{10} at all available stations.

area	type	month	n	FAC2	MB	NMB	RMSE	r	IOA
Rotterdam									
n.a.	industry	Januar	2146	0.70	-8.34	-0.38	12.73	0.50	0.44
n.a.	industry	Juli	2031	0.81	-3.73	-0.20	10.55	0.55	0.58

rural	background	Januar	744	0.69	-4.97	-0.28	11.06	0.67	0.57
rural	background	Juli	738	0.65	-3.62	-0.22	11.55	0.55	0.55
suburban	background	Januar	741	0.67	-6.52	-0.32	13.62	0.46	0.49
suburban	background	Juli	740	0.68	-0.64	-0.04	10.28	0.48	0.54
urban	backgorund	Januar	3662	0.70	-8.12	-0.37	14.35	0.58	0.52
urban	backgorund	Juli	3630	0.79	-2.07	-0.12	8.84	0.61	0.58
urban	traffic	Januar	3626	0.69	-9.69	-0.40	18.17	0.48	0.49
urban	traffic	Juli	4424	0.81	-2.82	-0.15	9.30	0.60	0.58
Nijmegen									
urban	traffic	Januar	739	0.70	-7.34	-0.32	20.78	0.44	0.58
urban	traffic	Juli	736	0.70	-1.24	-0.07	12.37	0.48	0.55
Antwerp									
n.a.	industrial	Januar	5943	0.87	-6.27	-0.27	12.12	0.65	0.58
n.a.	industrial	Juli	5944	0.89	-2.79	-0.15	8.42	0.65	0.60
suburban	background	Januar	2225	0.93	-4.39	-0.20	9.56	0.74	0.64
suburban	background	Juli	2171	0.93	-1.85	-0.11	7.08	0.68	0.62
urban	background	Januar	1474	0.90	-6.28	-0.26	10.99	0.72	0.59
urban	background	Juli	1484	0.83	-8.16	-0.33	33.43	0.21	0.59
urban	traffic	Januar	1452	0.85	-8.48	-0.32	14.53	0.70	0.58
urban	traffic	Juli	1479	0.83	-6.34	-0.28	12.01	0.62	0.56
Western Rhine-Ruhr area									
n.a.	industry	Januar	1991	0.65	-2.69	-0.11	21.97	0.36	0.28
n.a.	industry	Juli	1911	0.78	3.67	0.18	20.01	0.20	0.13
suburban	background	Januar	1838	0.76	-5.10	-0.24	12.17	0.43	0.49
suburban	background	Juli	1923	0.85	-2.04	-0.11	8.87	0.38	0.42
urban	backgorund	Januar	4583	0.76	-6.15	-0.27	13.15	0.49	0.50
urban	backgorund	Juli	4423	0.82	-3.59	-0.17	12.80	0.20	0.39
urban	traffic	Januar	5475	0.59	-11.97	-0.44	17.59	0.44	0.39
urban	traffic	Juli	5621	0.79	-6.08	-0.28	10.71	0.32	0.34

Additionally, we created a series of scatter plots for each urban domain, to visualize the match of hourly modeled versus hourly measured values (Figures 4-7).

Rotterdam NO_2 hourly

Rotterdam PM_{10} hourly

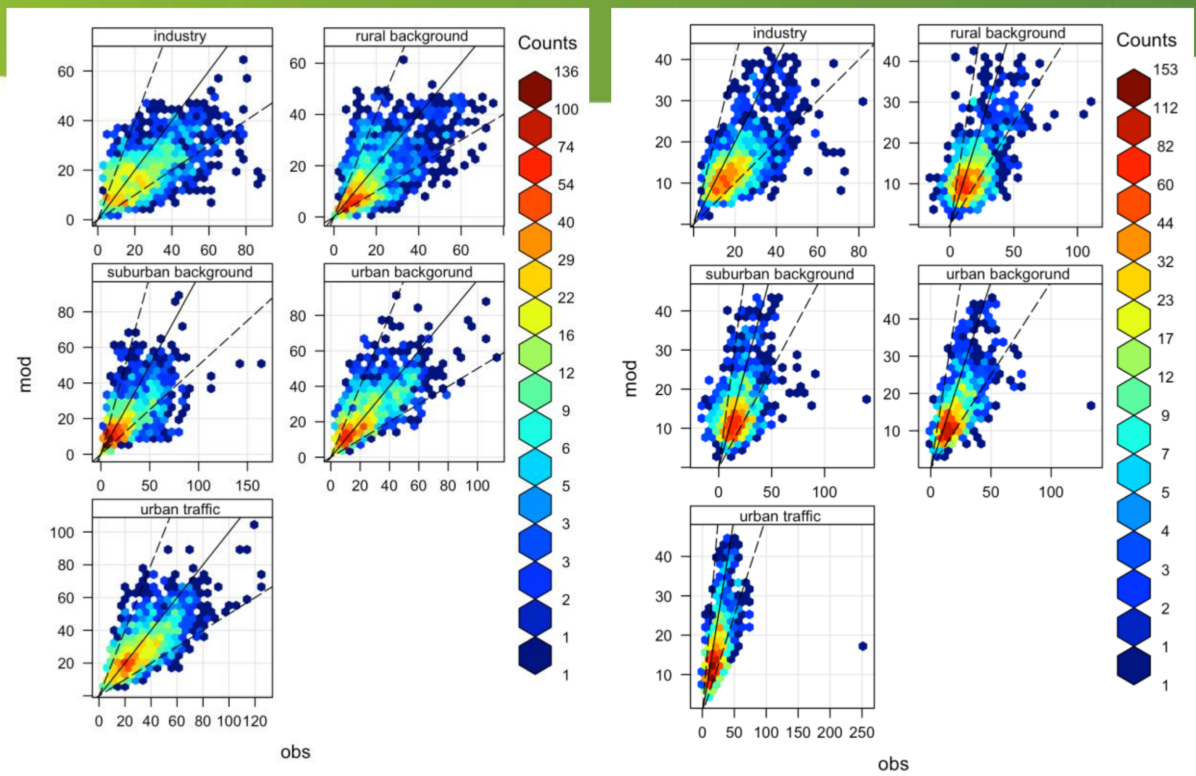


Figure 1:Scatter plots of hourly measured vs. modelled NO_2 and PM_{10} values in Rotterdam.

Nijmegen NO_2 hourly **Nijmegen PM_{10} hourly**

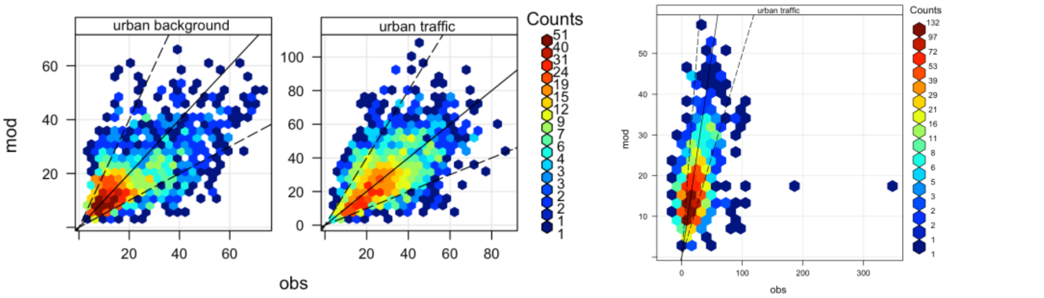


Figure 2: Scatter plots of hourly measured vs. modelled NO_2 and PM_{10} values in Nijmegen.

Antwerp NO_2 hourly **Antwerp PM_{10} hourly**

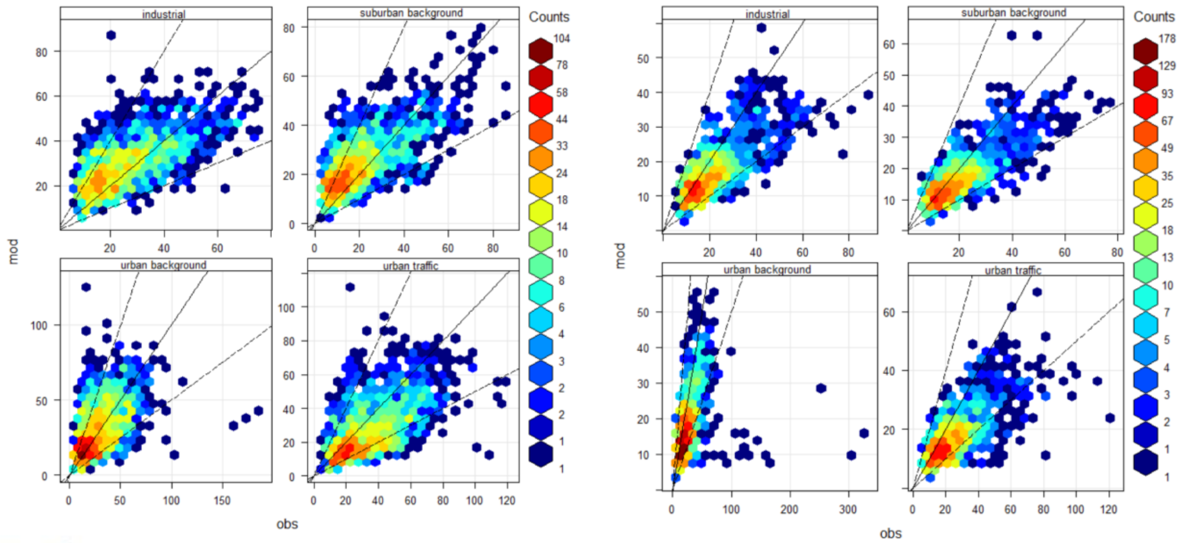


Figure 3: Scatter plots of hourly measured vs. modelled NO_2 and PM_{10} values in Antwerp.

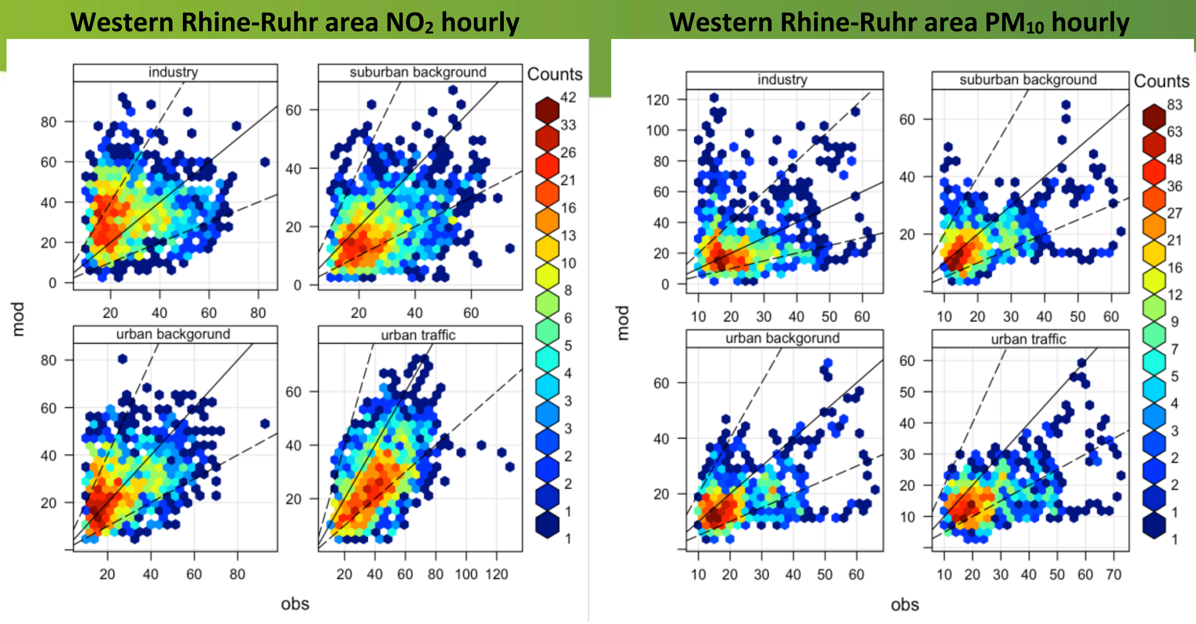
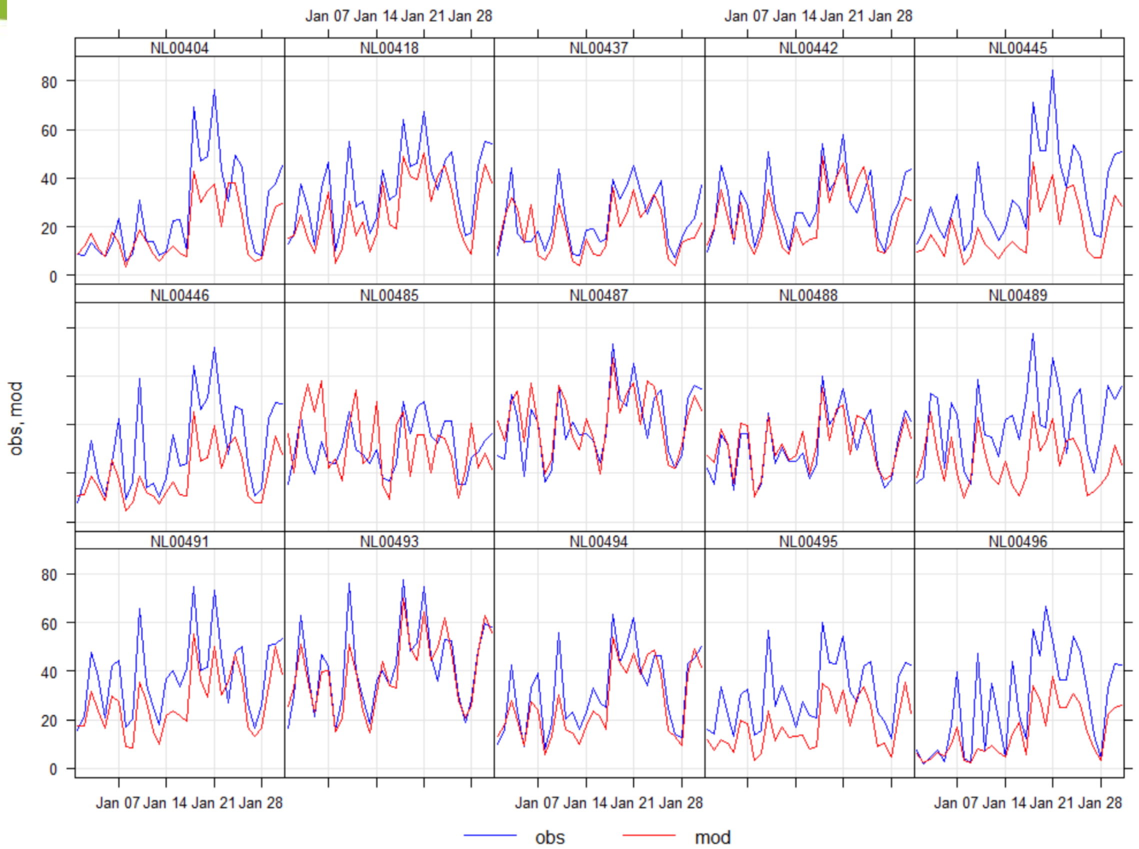


Figure 4: Scatter plots of hourly measured vs. modelled NO_2 and PM_{10} values in Western Rhine-Ruhr area.

Followed by the evaluation of hourly values, we also compared daily measured vs. modeled values (in Figures 8-15).

Rotterdam January 2019 NO_2 daily time series [µg/m³]



Rotterdam July 2019 NO_2 daily time series [µg/m³]

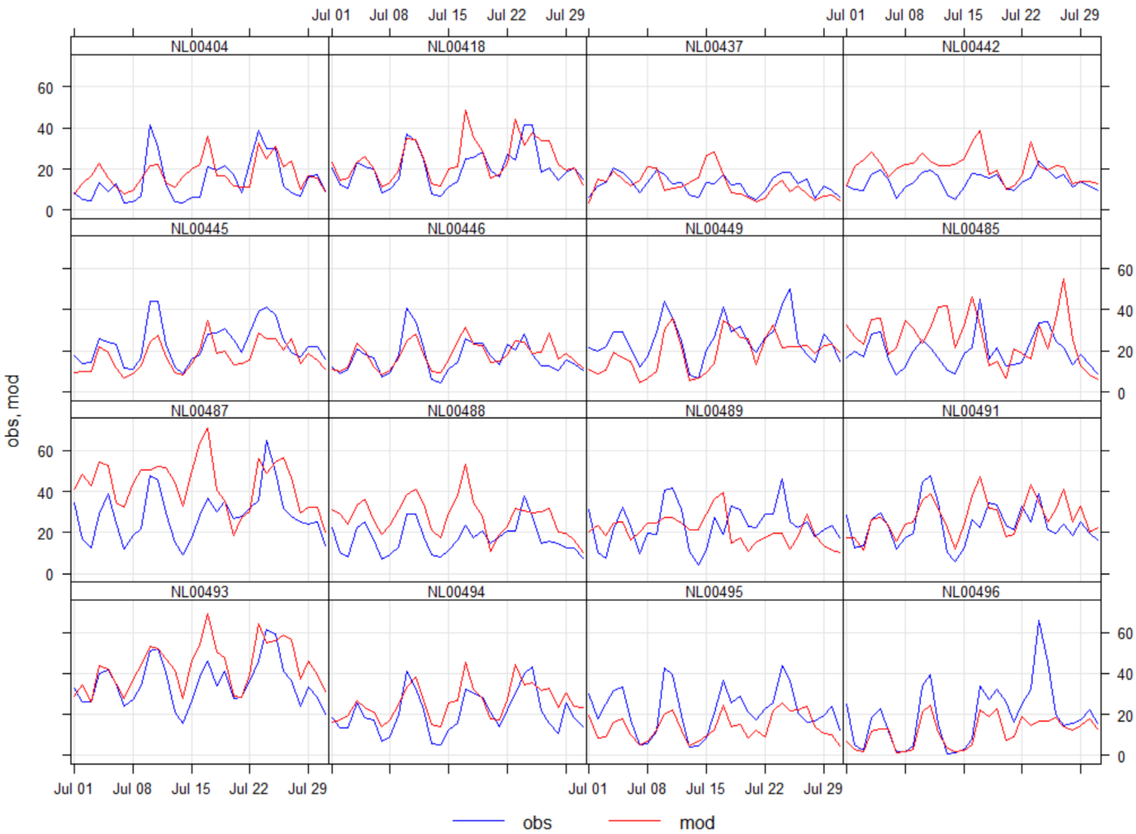
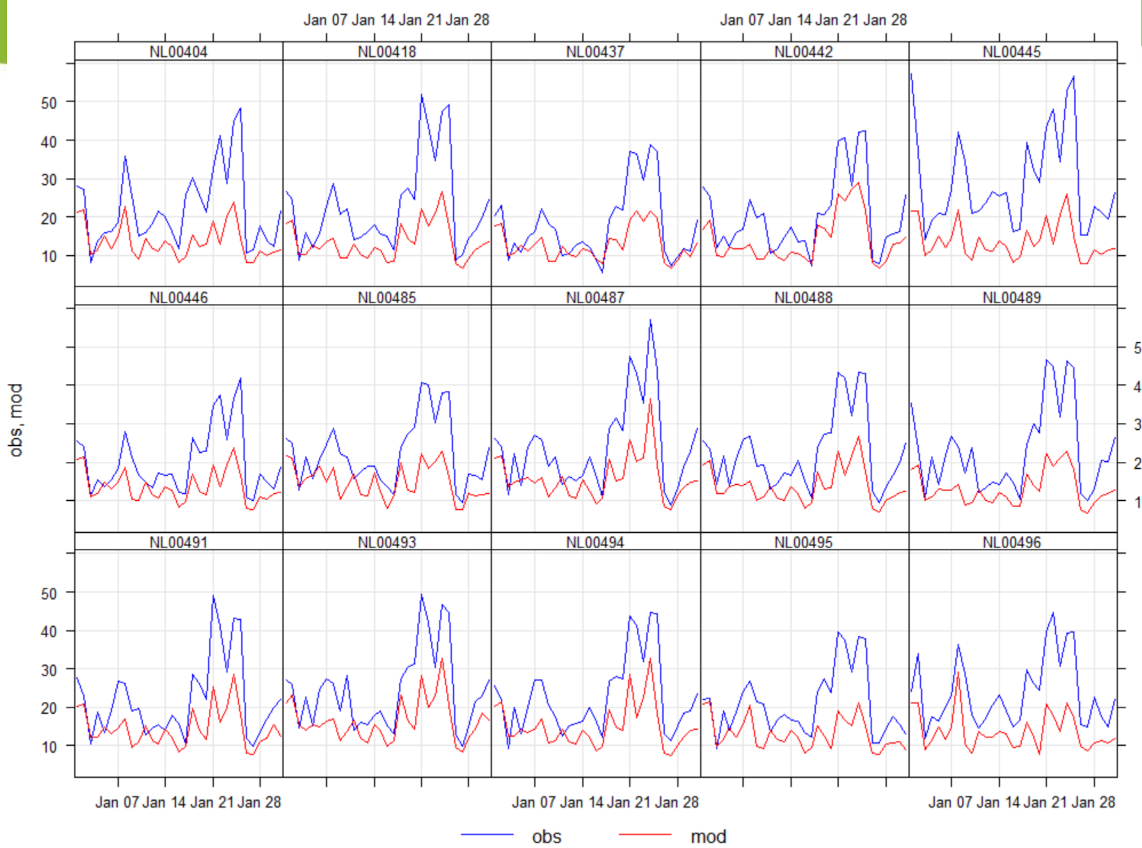


Figure 5: Time series in Jan/Jul 2019 of daily NO_2 concentrations for all applied measurement sites in Rotterdam.

Rotterdam January 2019 PM_{10} daily time series [µg/m³]



Rotterdam July 2019 PM_{10} daily time series [µg/m³]

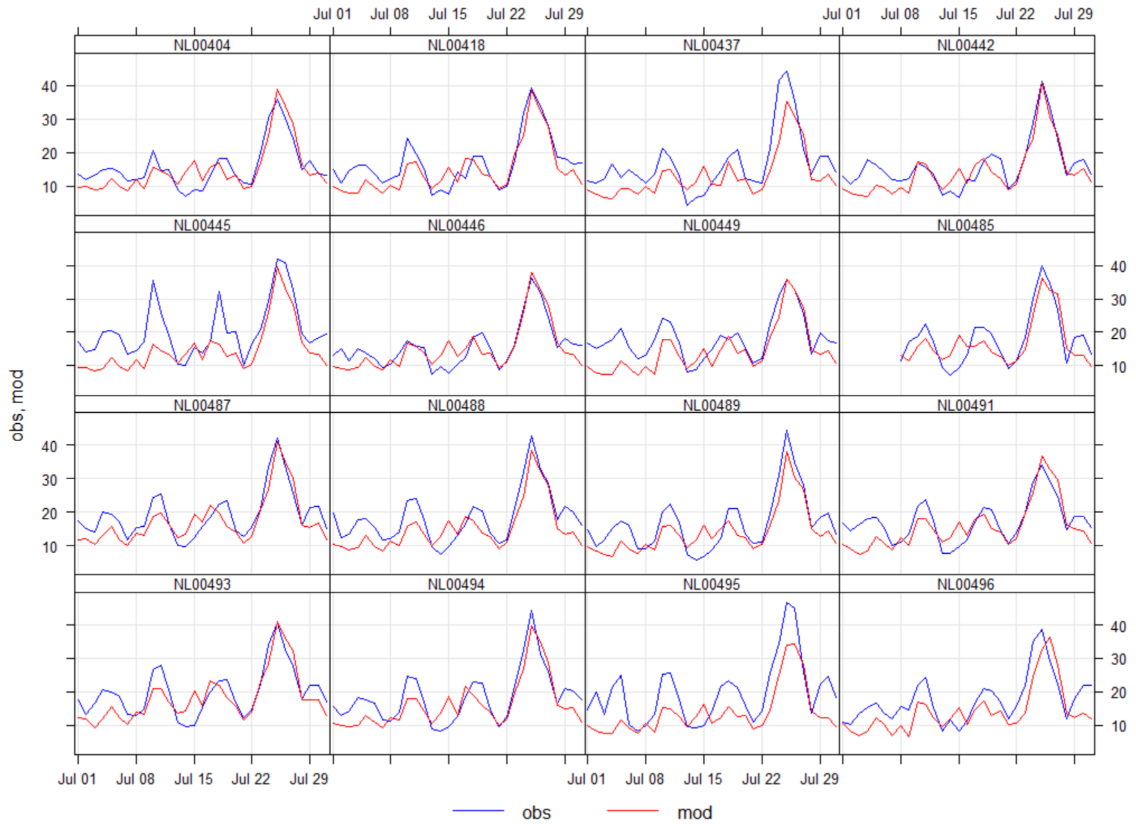
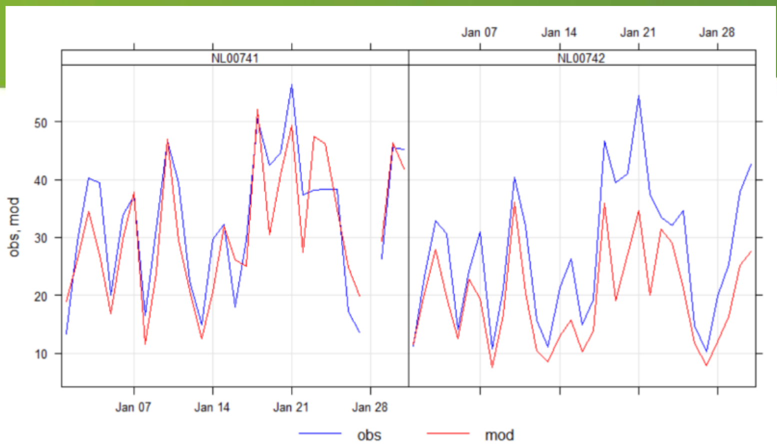


Figure 6: Time series in Jan/Jul 2019 of daily PM_{10} concentrations for all applied measurement sites in Rotterdam.

Nijmegen January 2019 NO_2 daily time series [µg/m³]



Nijmegen July 2019 NO_2 daily time series [µg/m³]

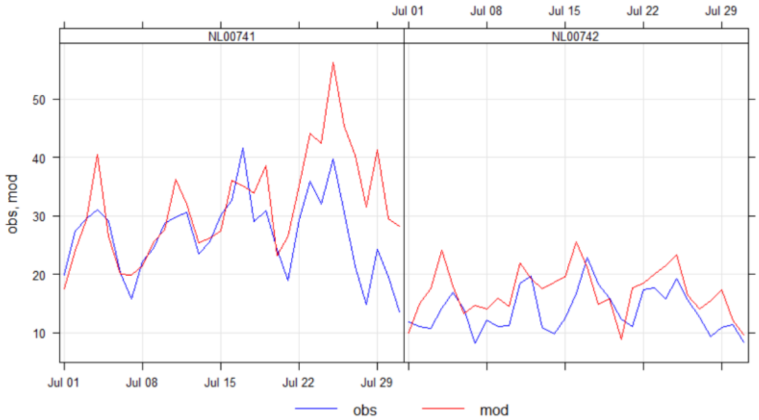
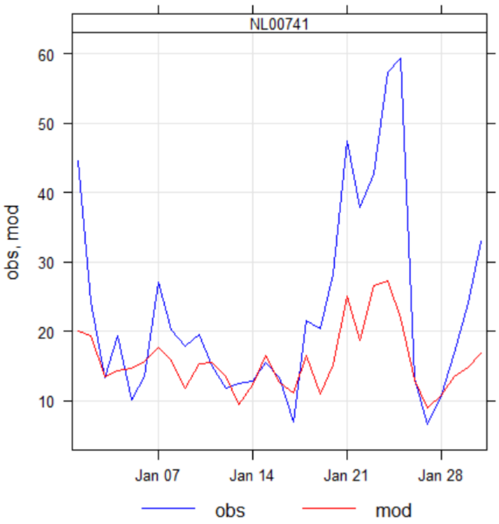


Figure 7: Time series in Jan/Jul 2019 of daily NO_2 concentrations for all applied measurement sites in Nijmegen.

Nijmegen January 2019 PM_{10} daily time series [µg/m³]



Nijmegen July 2019 PM_{10} daily time series [µg/m³]

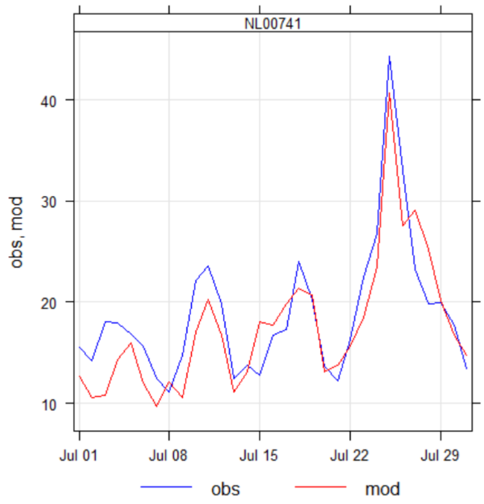
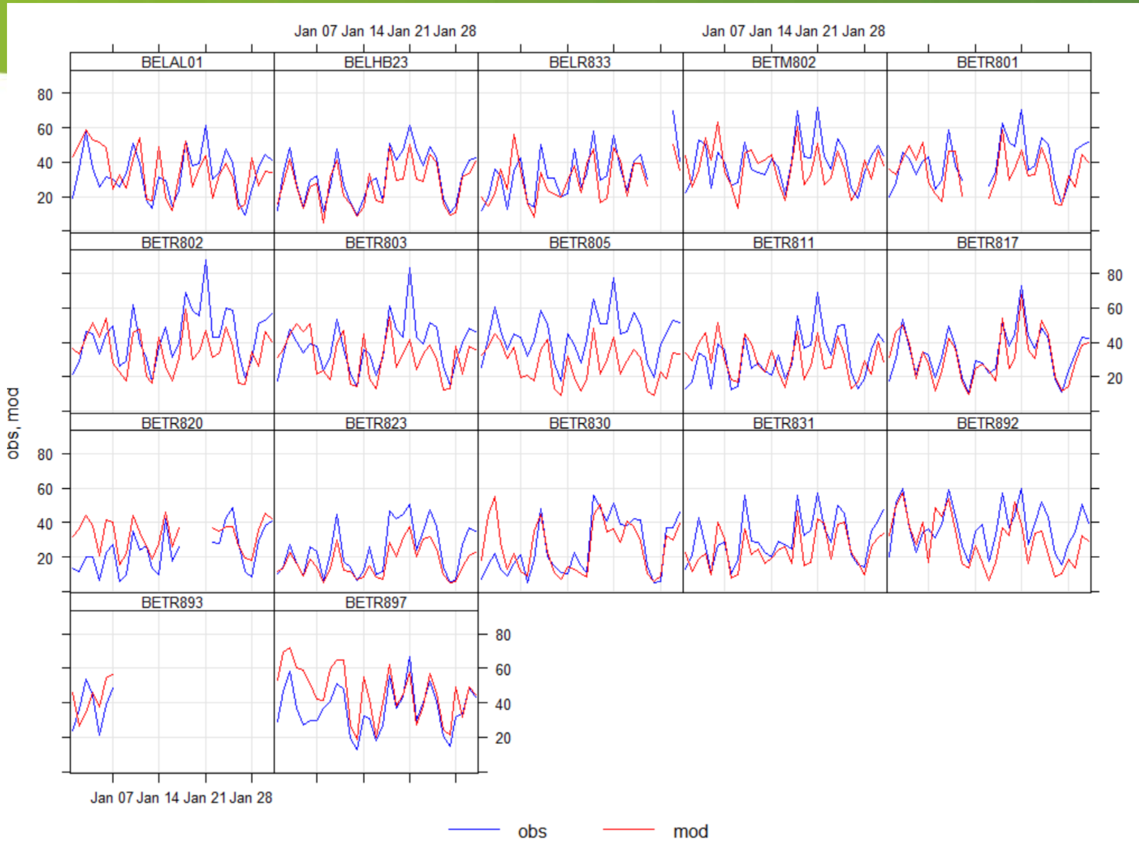


Figure 8: Time series in Jan/Jul 2019 of daily PM_{10} concentrations for all applied measurement sites in Nijmegen.

Antwerp January 2019 NO_2 daily time series [µg/m³]



Antwerp July 2019 NO_2 daily time series [µg/m³]

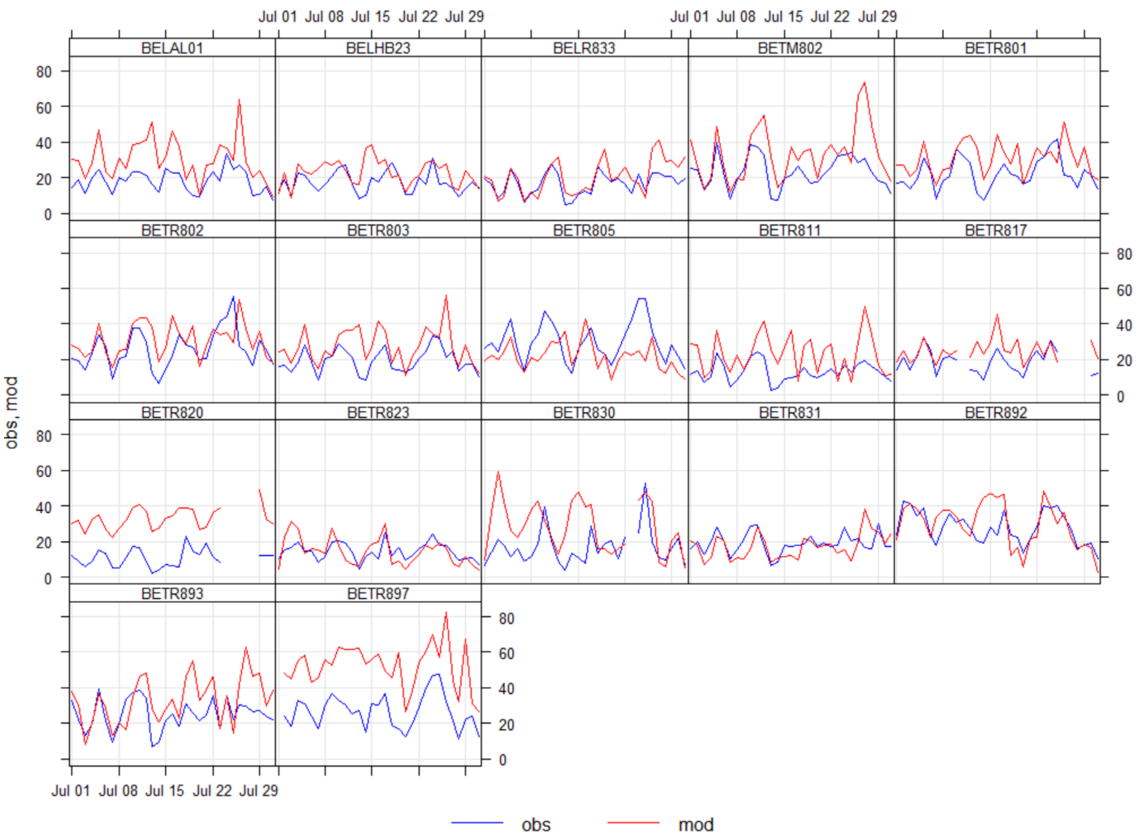
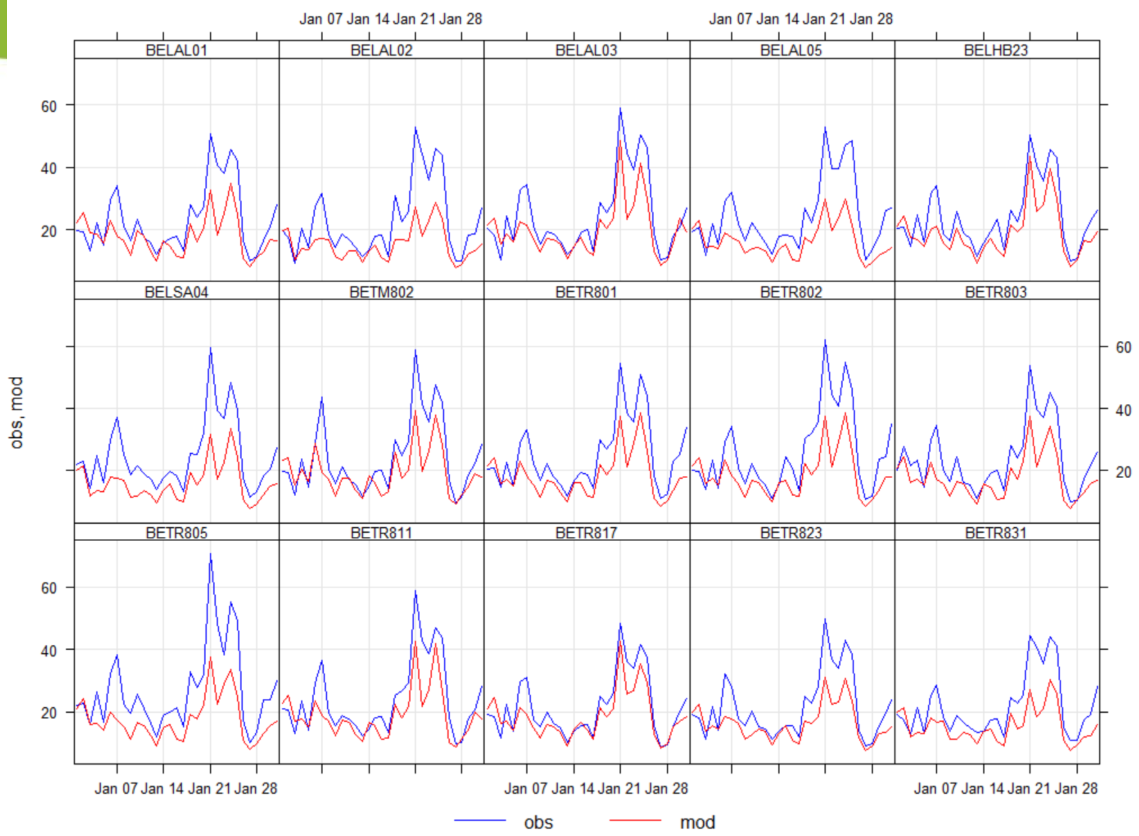


Figure 9: Time series in Jan/Jul 2019 of daily NO_2 concentrations for all applied measurement sites in Antwerp.

Antwerp January 2019 PM_{10}daily time series [µg/m³]



Antwerp July 2019 PM_{10} daily time series [µg/m³]

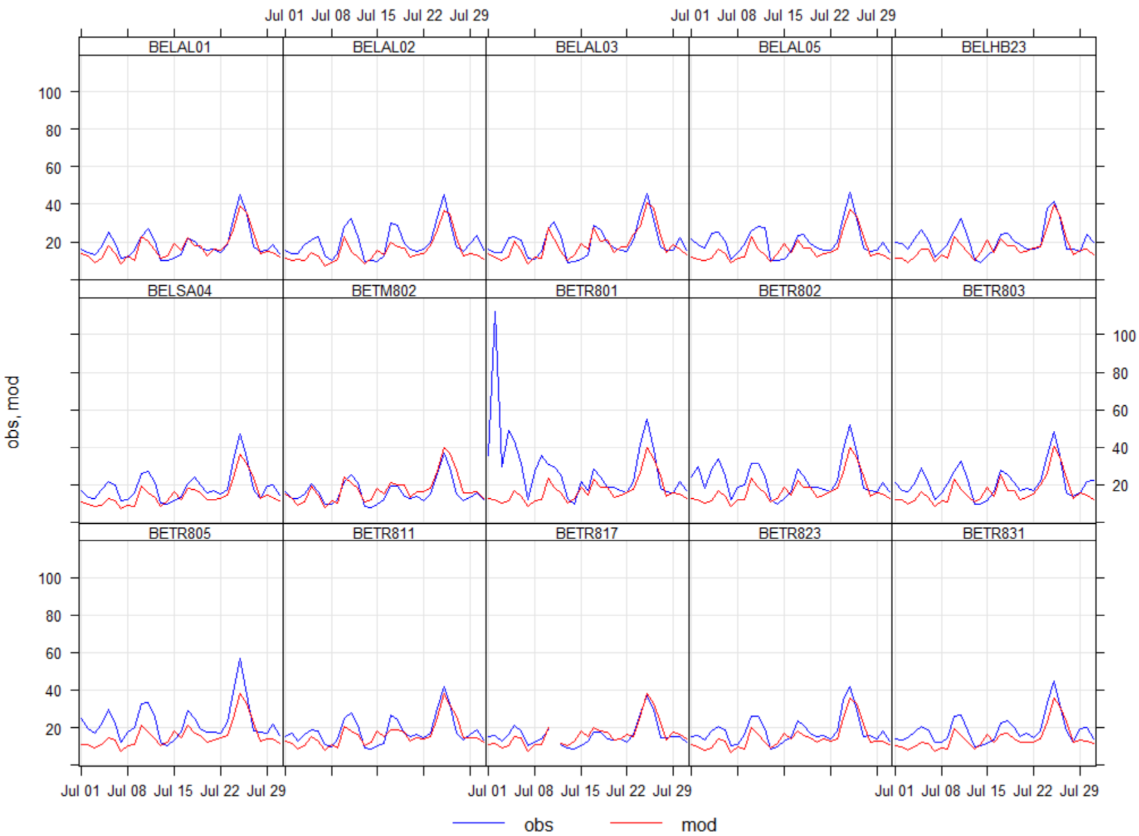
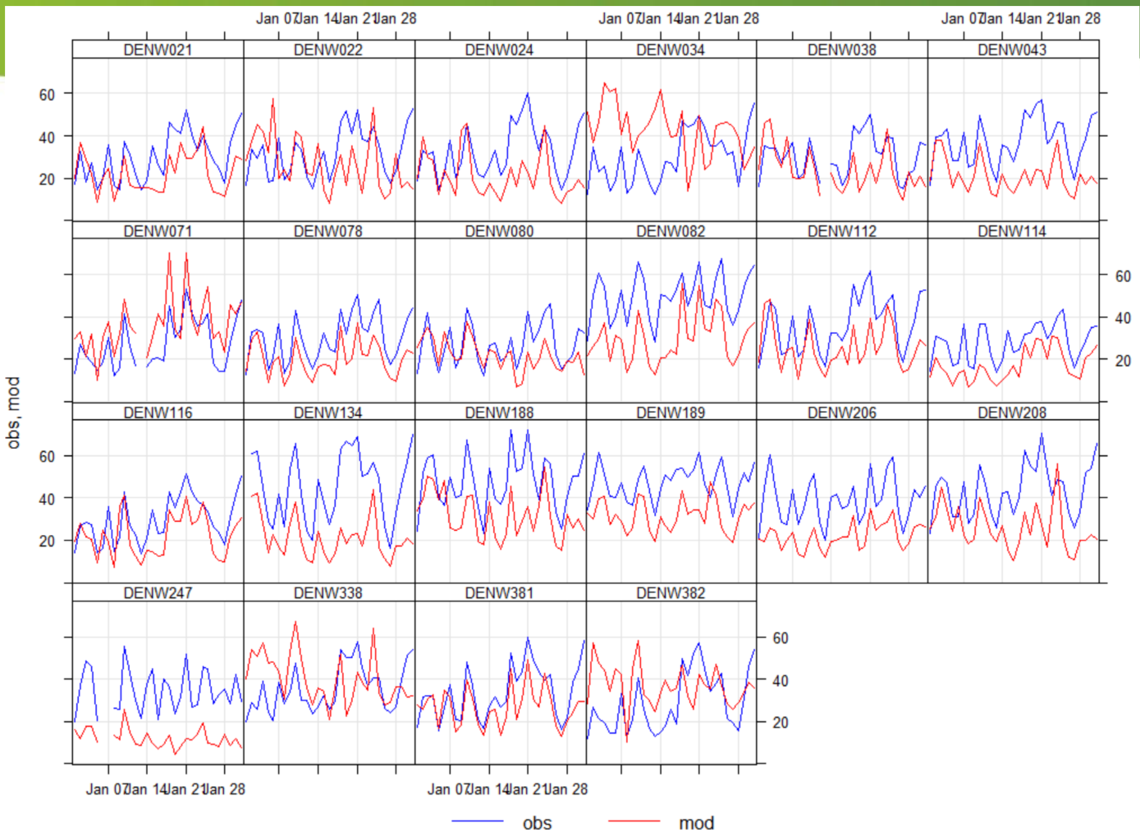


Figure 10: Time series in Jan/Jul 2019 of daily PM_{10} concentrations for all applied measurement sites in Antwerp.

Western Rhine-Ruhr area January 2019 NO_2 daily time series [µg/m³]



Western Rhine-Ruhr area July 2019 NO_2 daily time series [µg/m³]

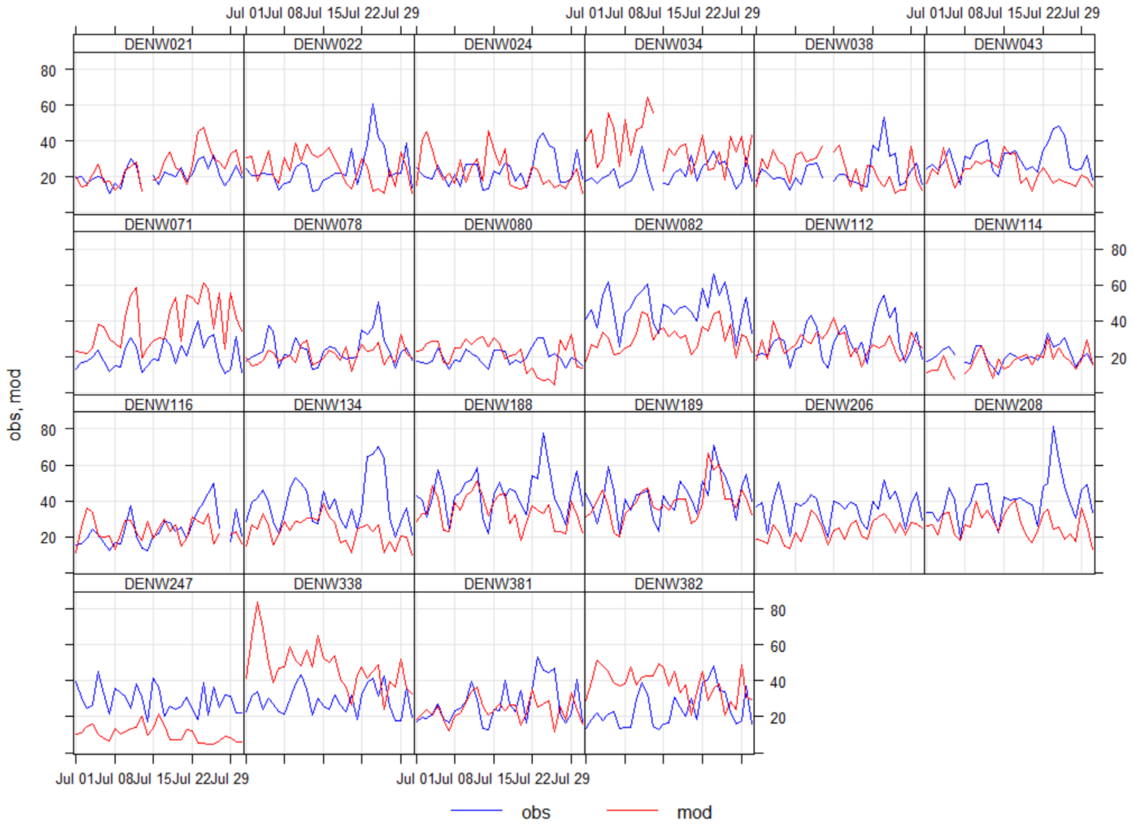
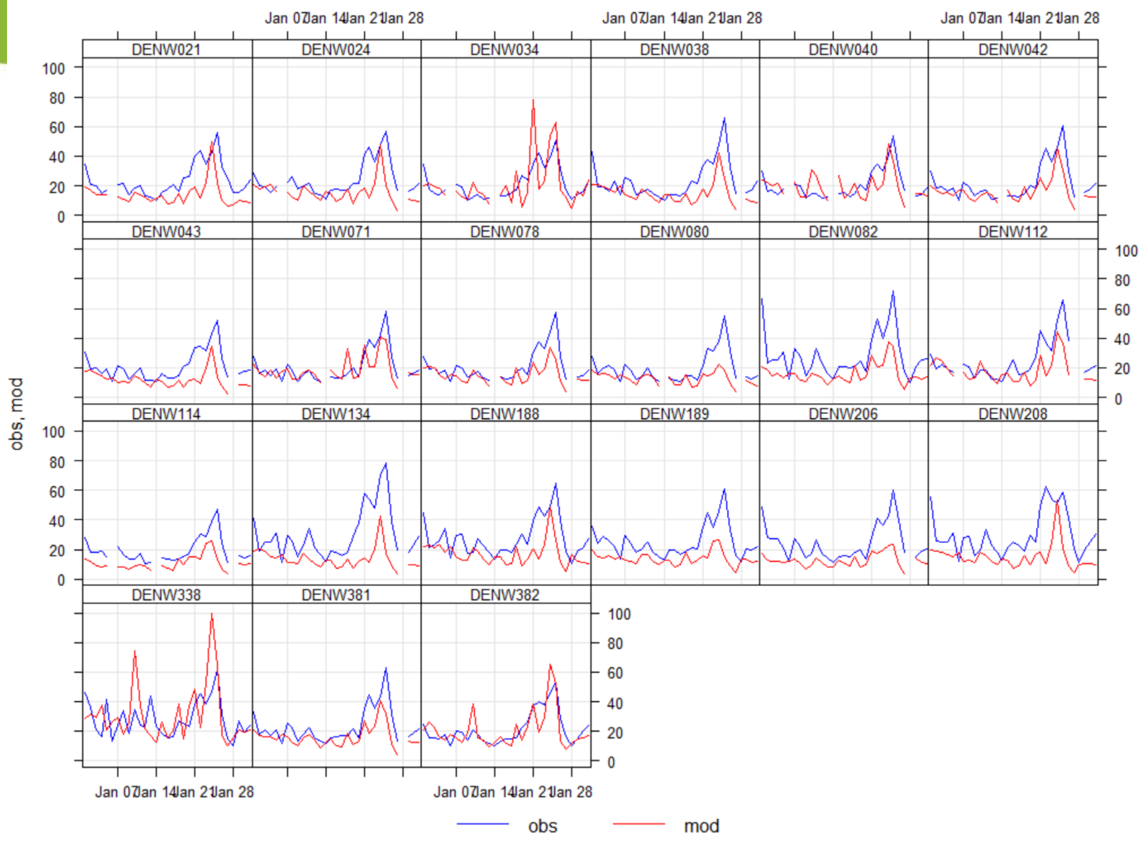


Figure 11: Time series in Jan/Jul 2019 of daily NO_2 concentrations for all applied measurement sites in Western Rhine-Ruhr area.

Western Rhine-Ruhr area January 2019 PM_{10} daily time series [µg/m³]



Western Rhine-Ruhr area July 2019 PM_{10} daily time series [µg/m³]

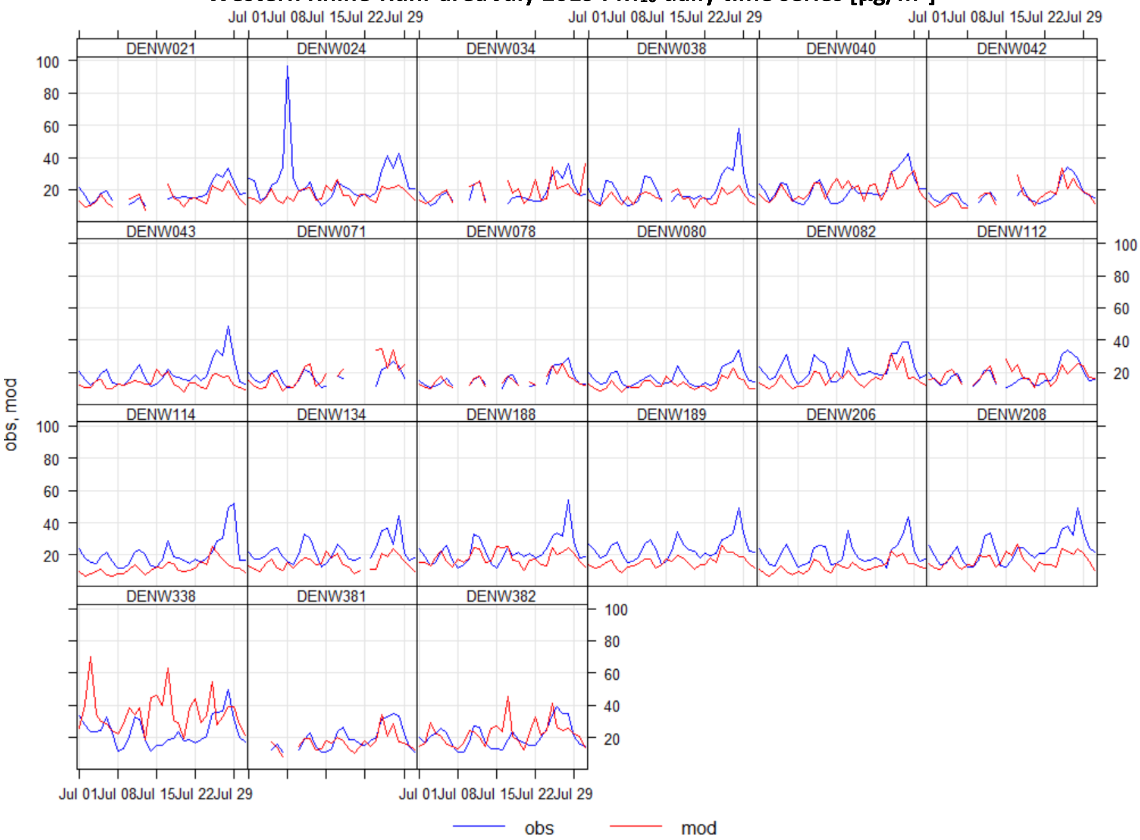


Figure 12: Time series in Jan/Jul 2019 of daily PM_{10} concentrations for all applied measurement sites in Western Rhine-Ruhr area.

In the following, we present maps of simulated air pollutant concentrations as monthly averages compared with monthly means at measurement sites in all urban domains (Figures 16-19).

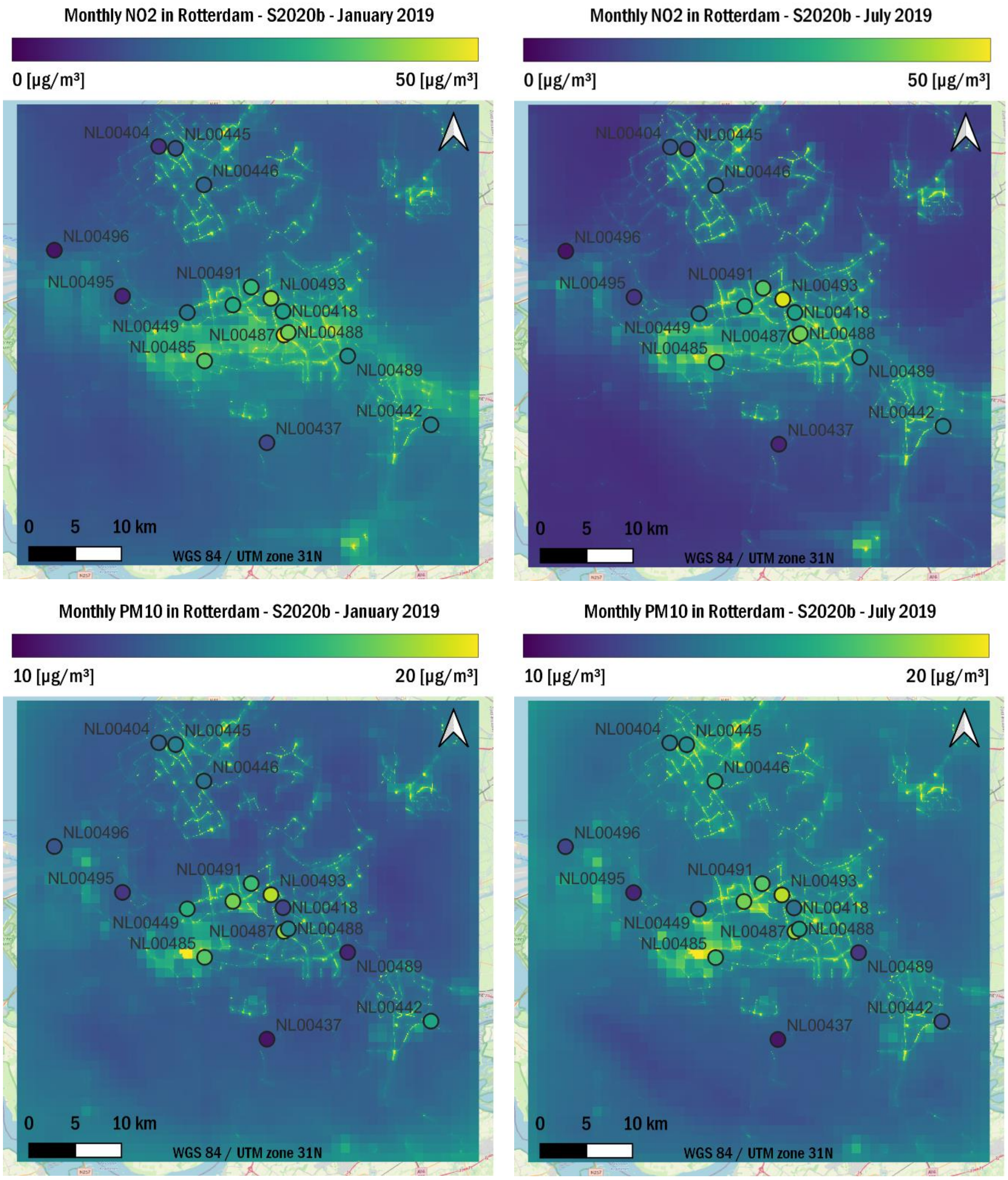


Figure 13: Monthly modelled NO_2 and PM_{10} in Rotterdam with inland shipping scenario S2020b. The colored dots represent monthly measured values at the respective measurement site and follow the same value range.

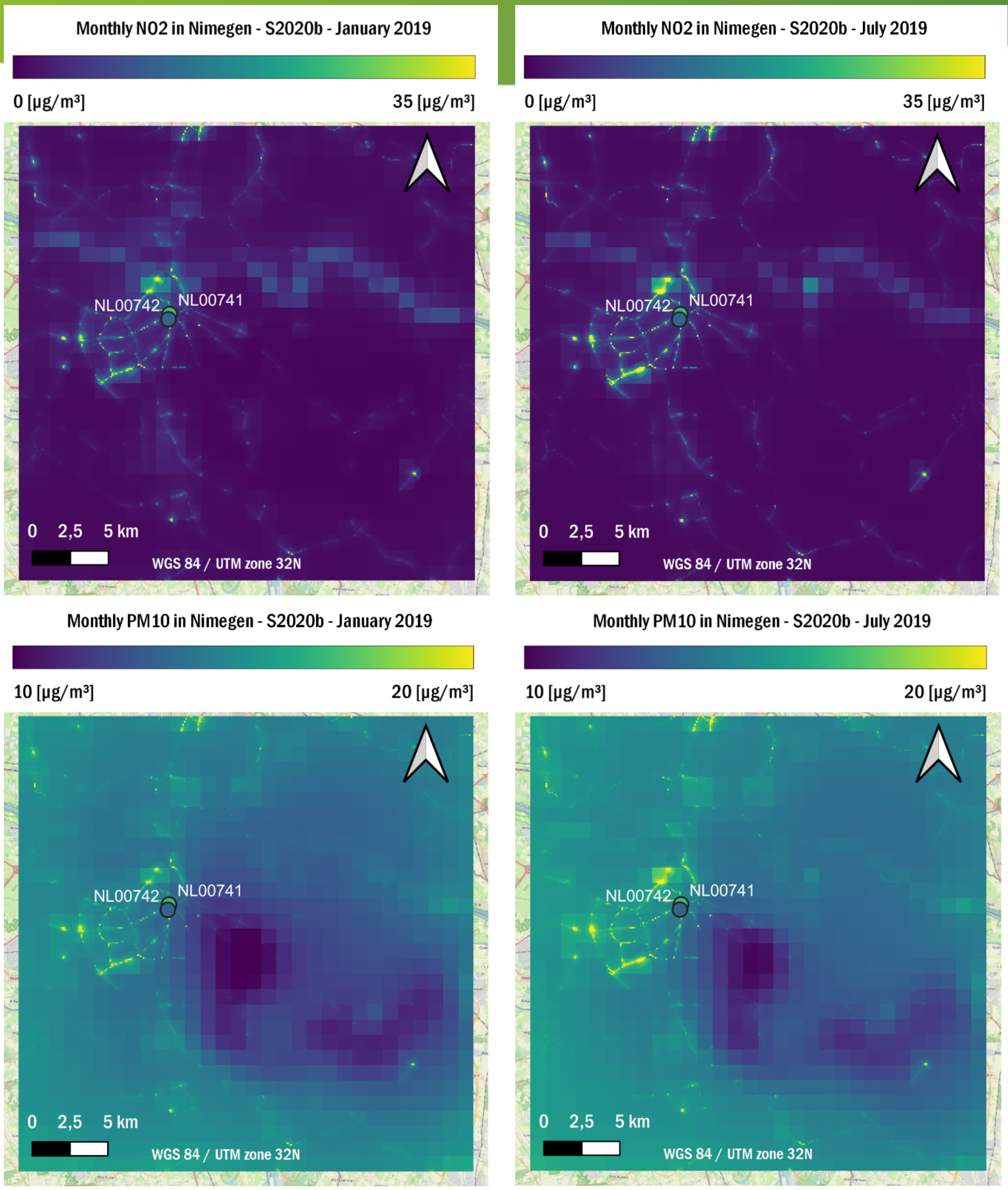


Figure 14: Monthly modelled NO_2 and PM_{10} in Nijmegen with inland shipping scenario S2020b. The colored dots represent monthly measured values at the respective measurement site and follow the same value range.

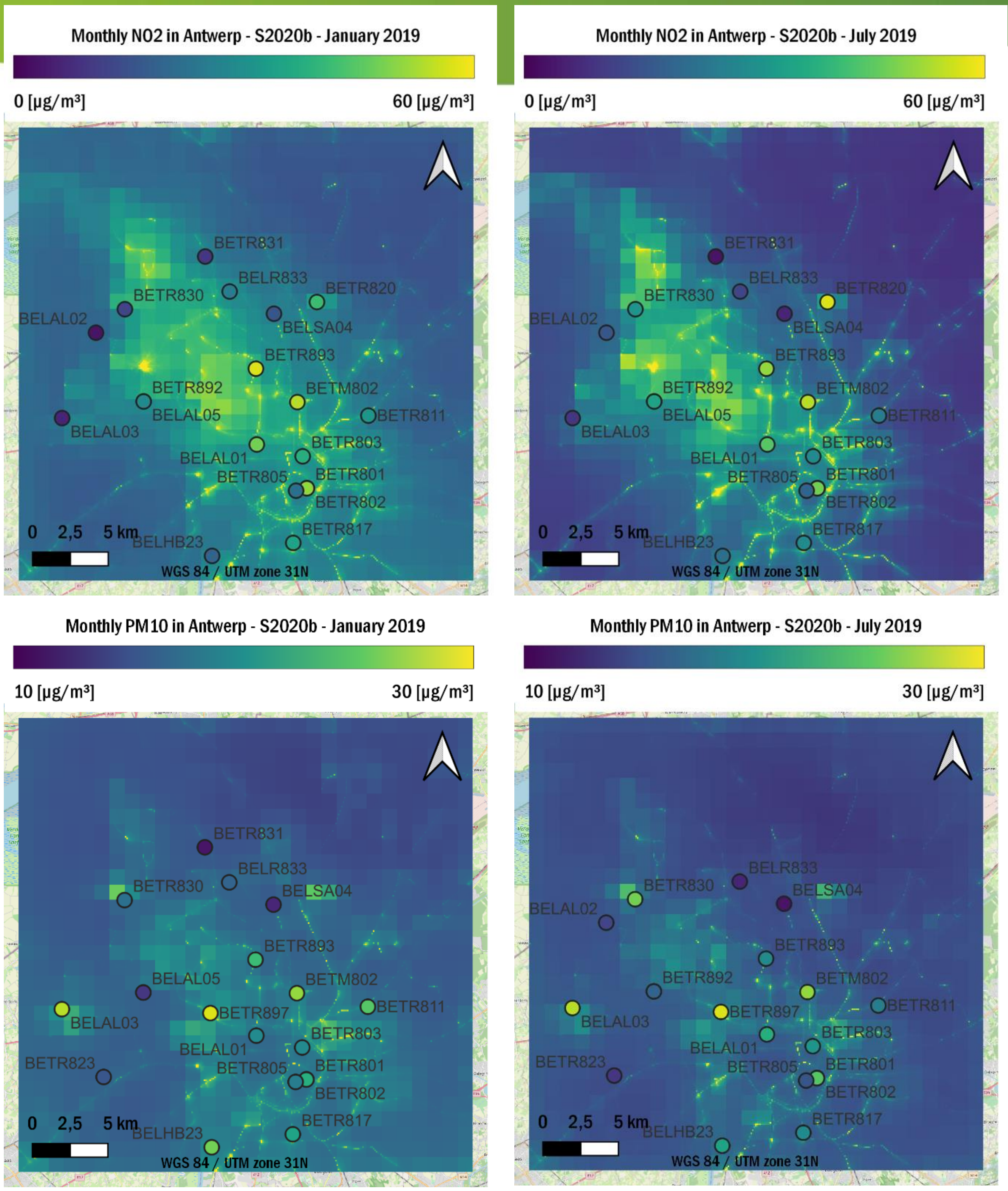


Figure 15: Monthly modelled NO_2 and PM_{10} in Antwerp with inland shipping scenario S2020b. The colored dots represent monthly measured values at the respective measurement site and follow the same value range.

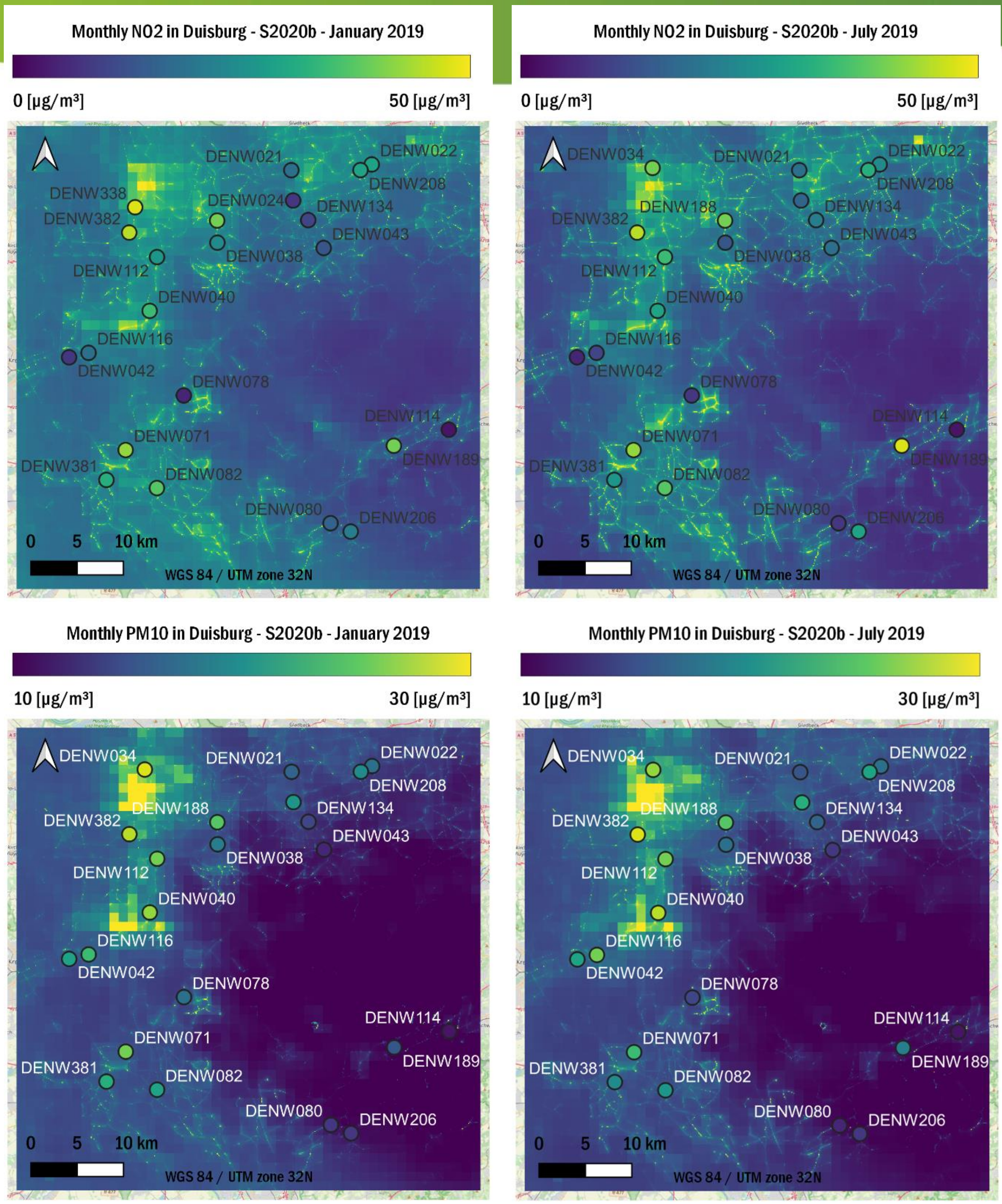


Figure 16: Monthly modelled NO_2 and PM_{10} in Western Rhine-Ruhr area with inland shipping scenario S2020b. The colored dots represent monthly measured values at the respective measurement site and follow the same value range.

To illustrate the impact of inland shipping emissions under current conditions, we plotted the absolute and relative impacts of inland shipping scenario emissions in S2020b.

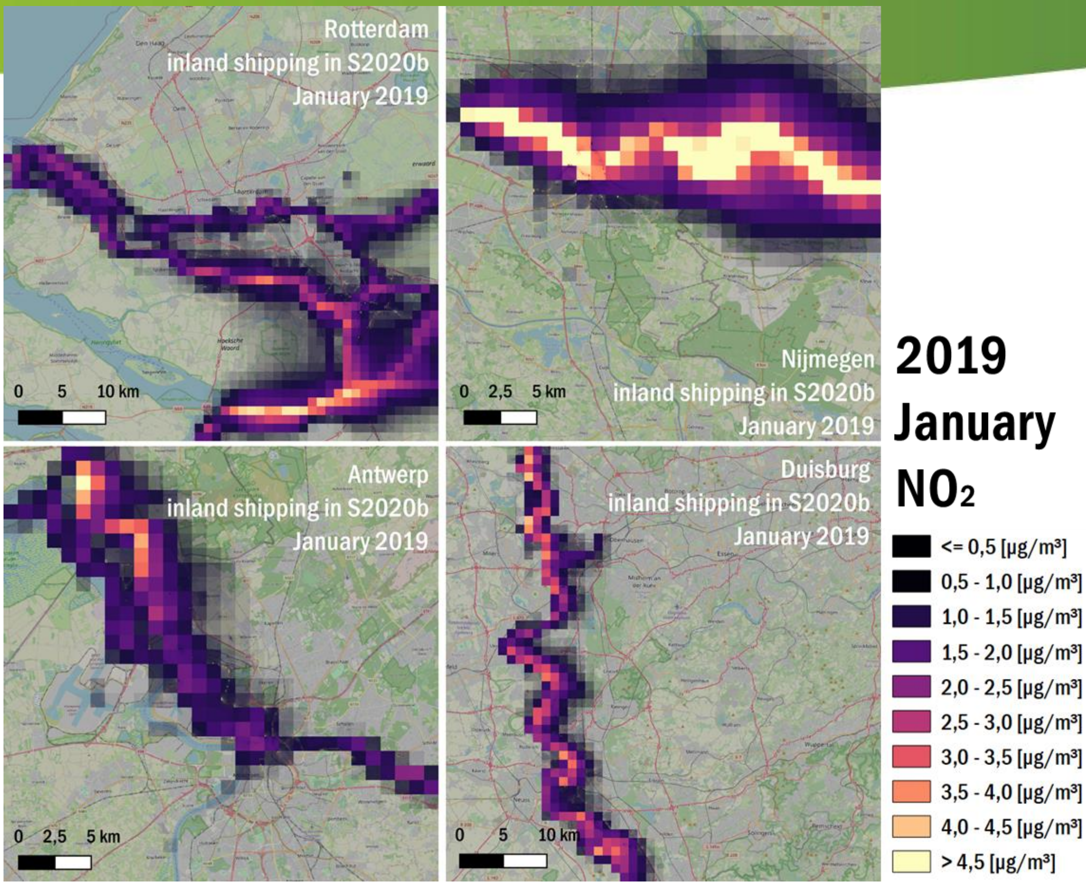


Figure 17: Absolute impact of S2020b inland shipping NO_2 emissions in January 2019.

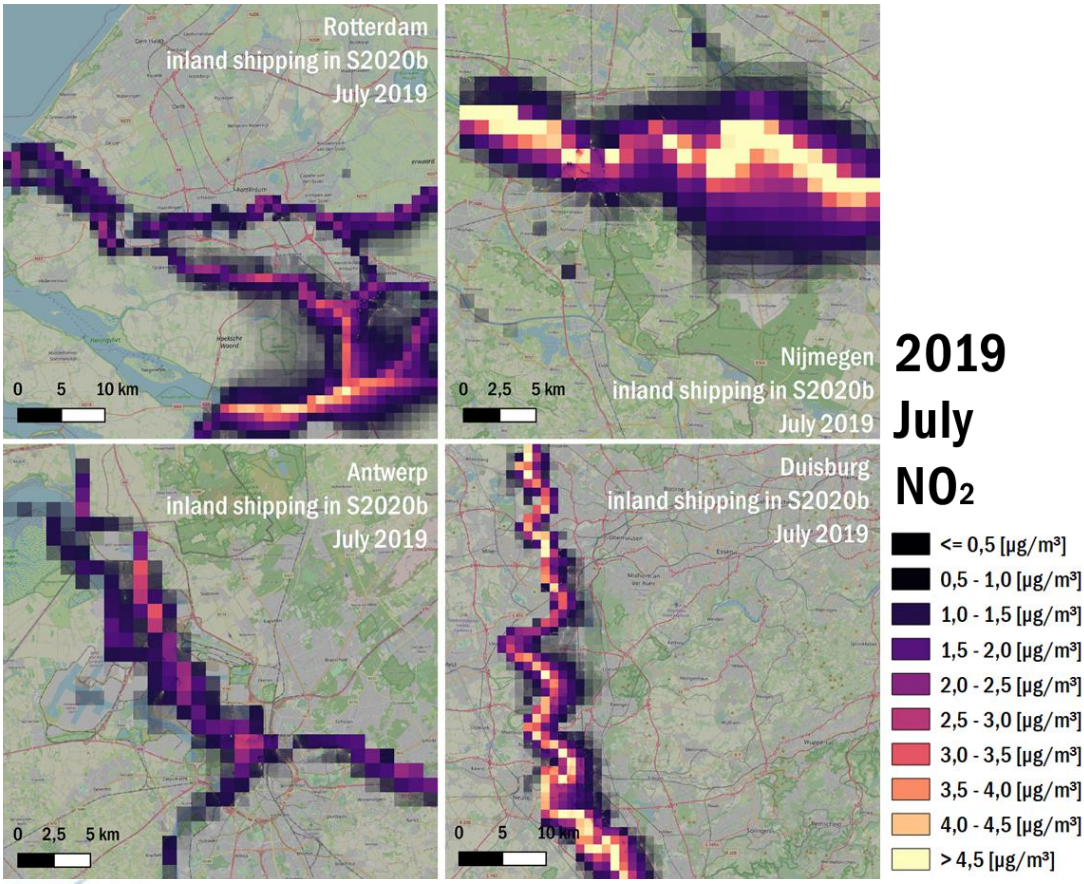


Figure 18: Absolute impact of S2020b inland shipping NO_2 emissions in July 2019.

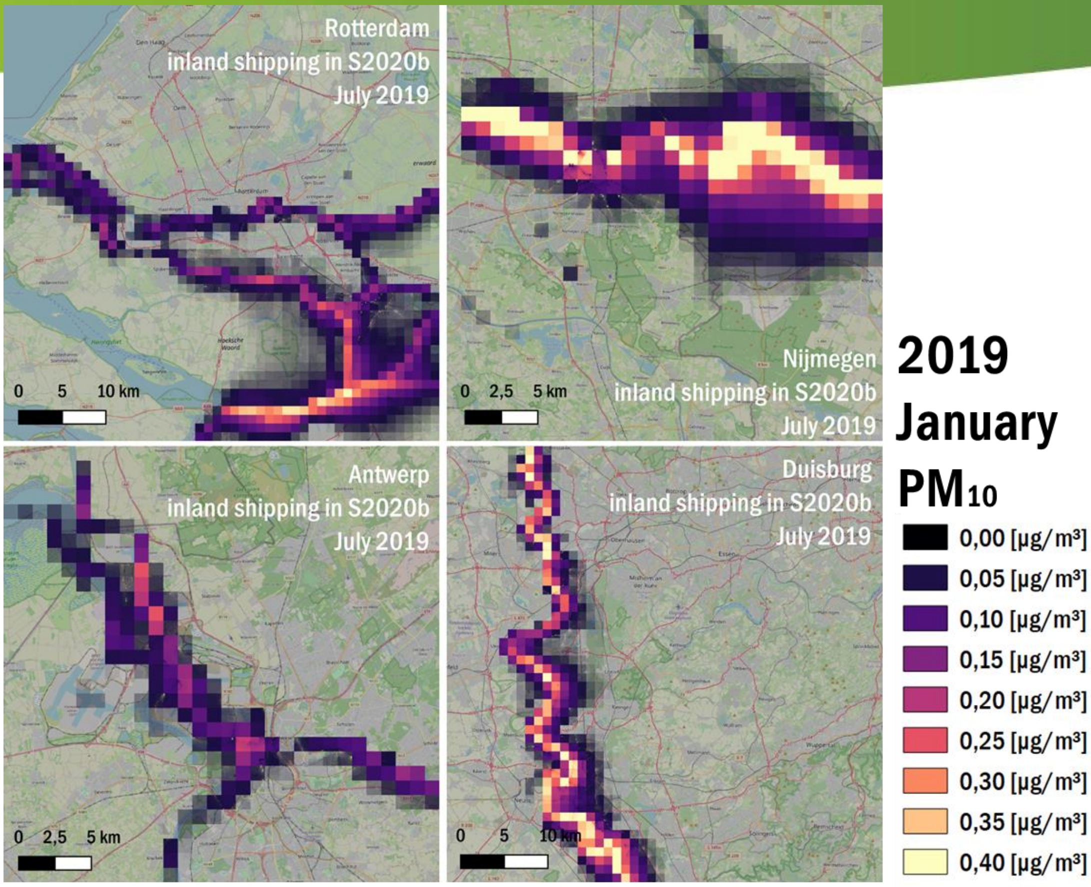


Figure 19: Absolute impact of S2020b inland shipping PM_{10} emissions in January 2019.

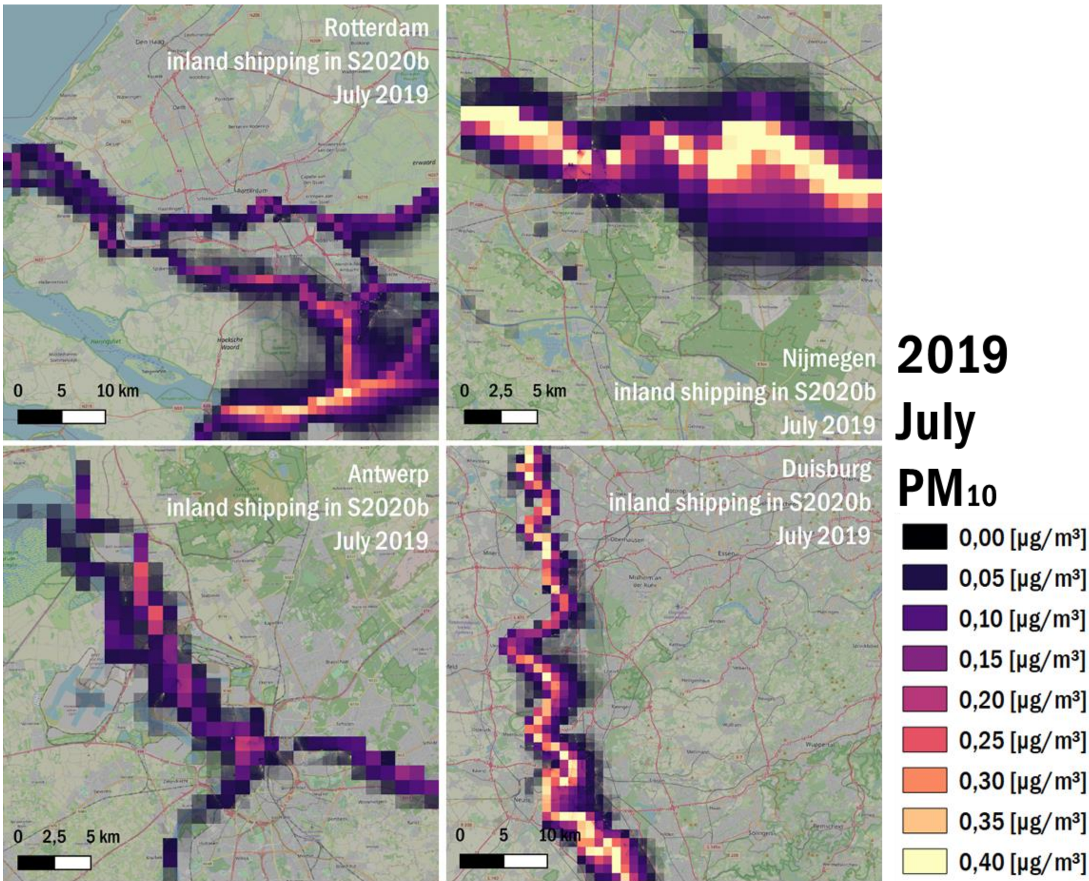


Figure 20: Absolute impact of S2020b inland shipping PM_{10} emissions in July 2019.

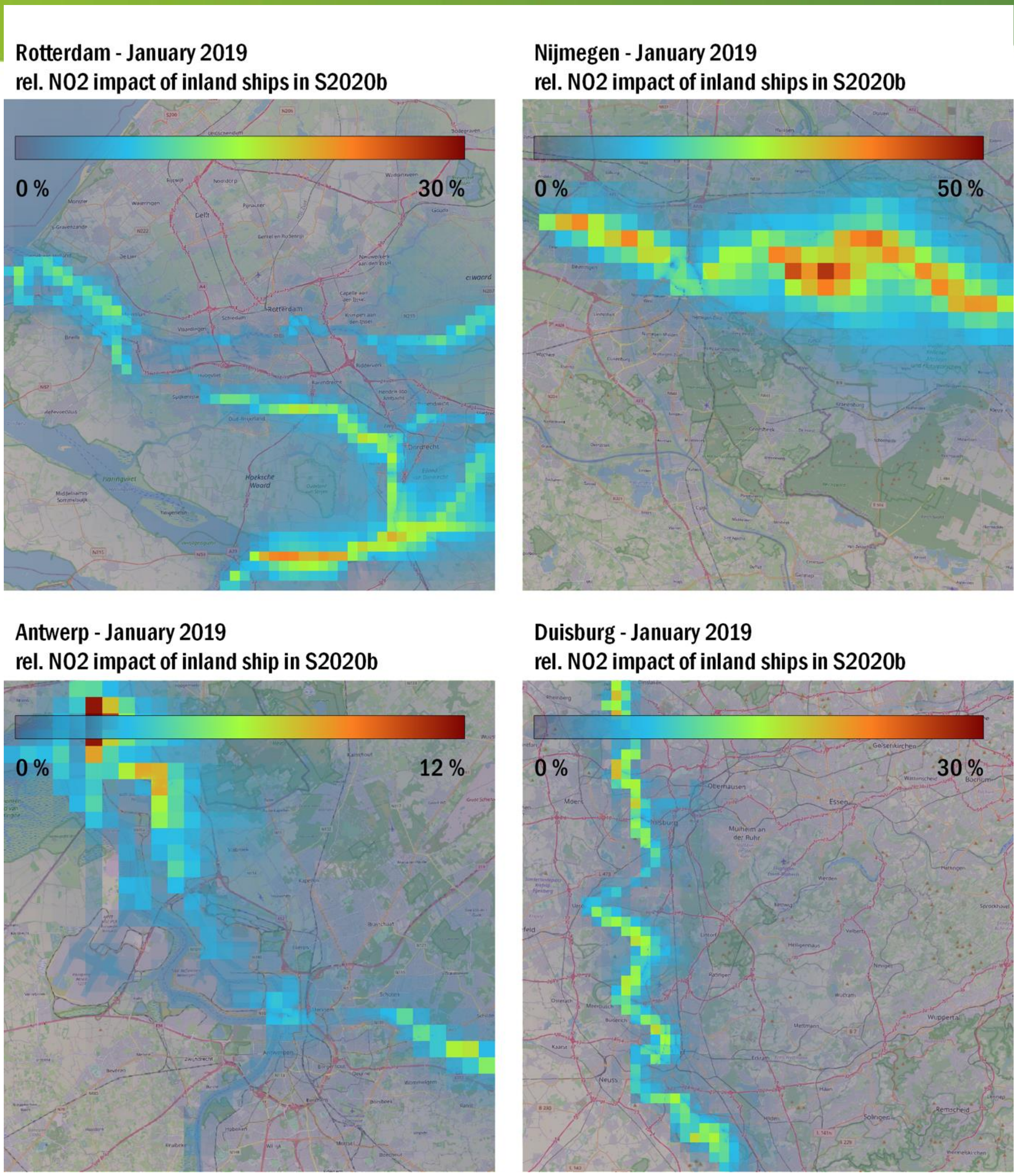


Figure 21: Relative impact of S2020b inland shipping NO_2 emissions in January 2019.

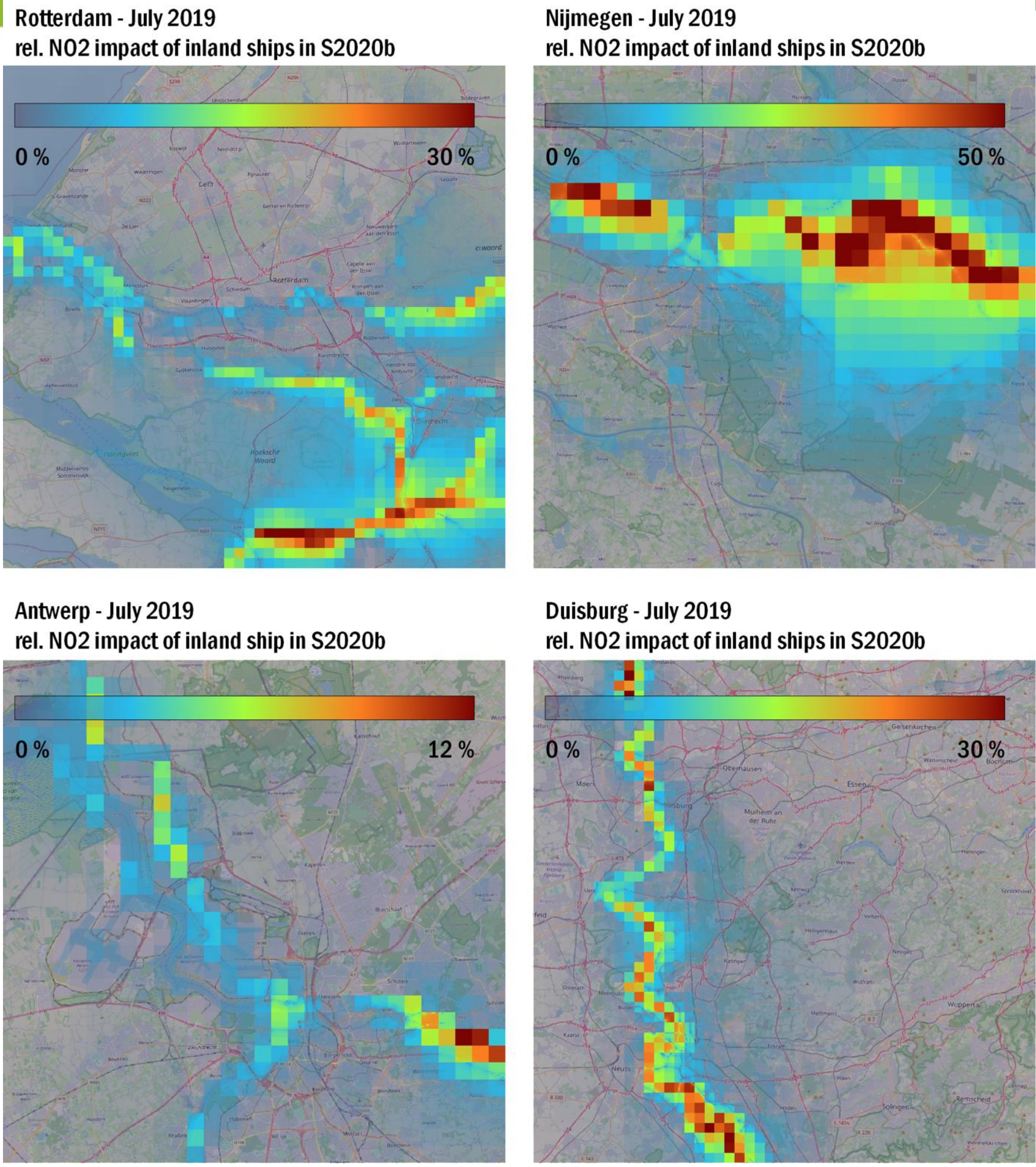


Figure 22: Relative impact of S2020b inland shipping NO_2 emissions in July 2019.

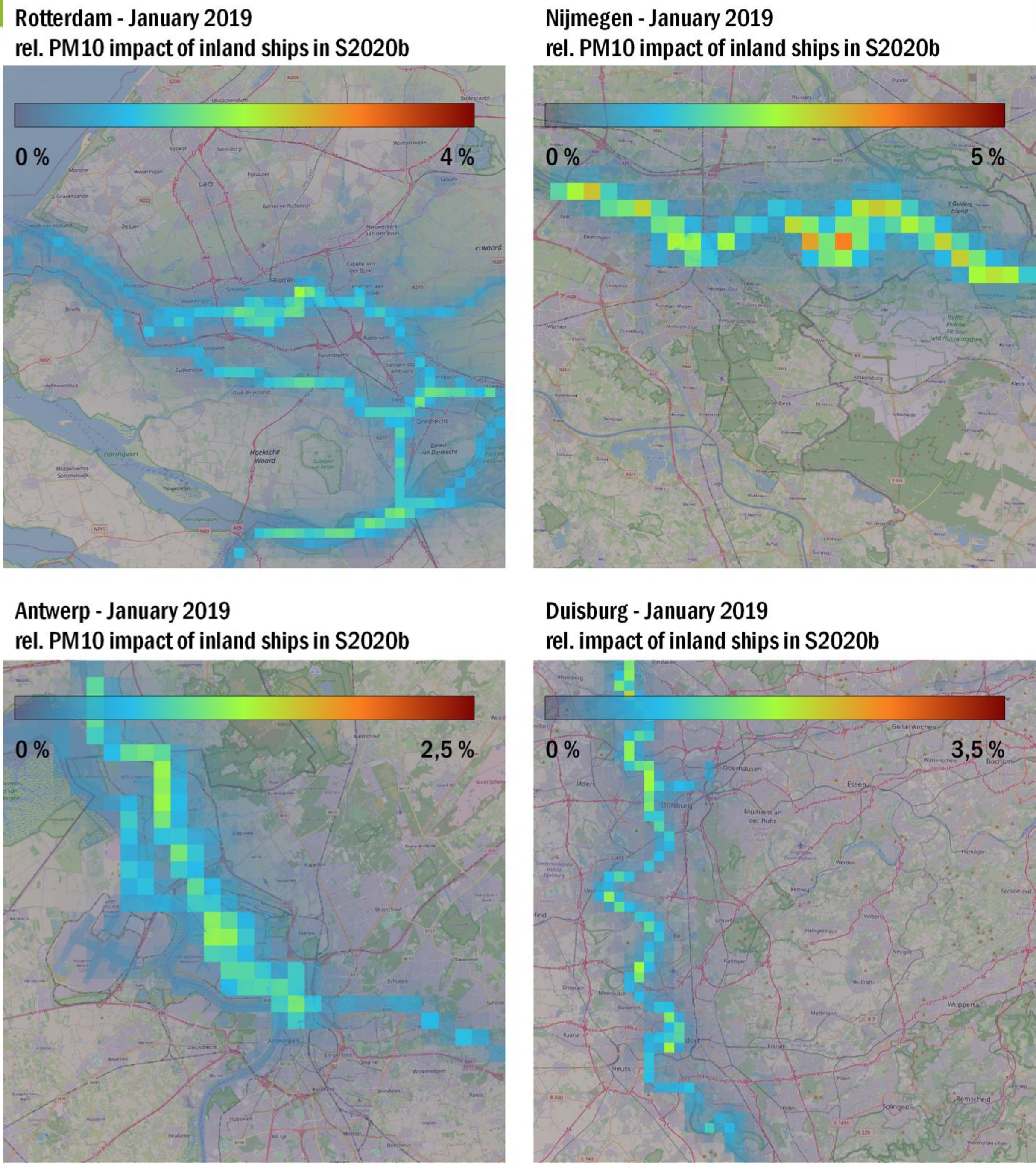


Figure 23: Relative impact of S2020b inland shipping PM_{10} emissions in January 2019.

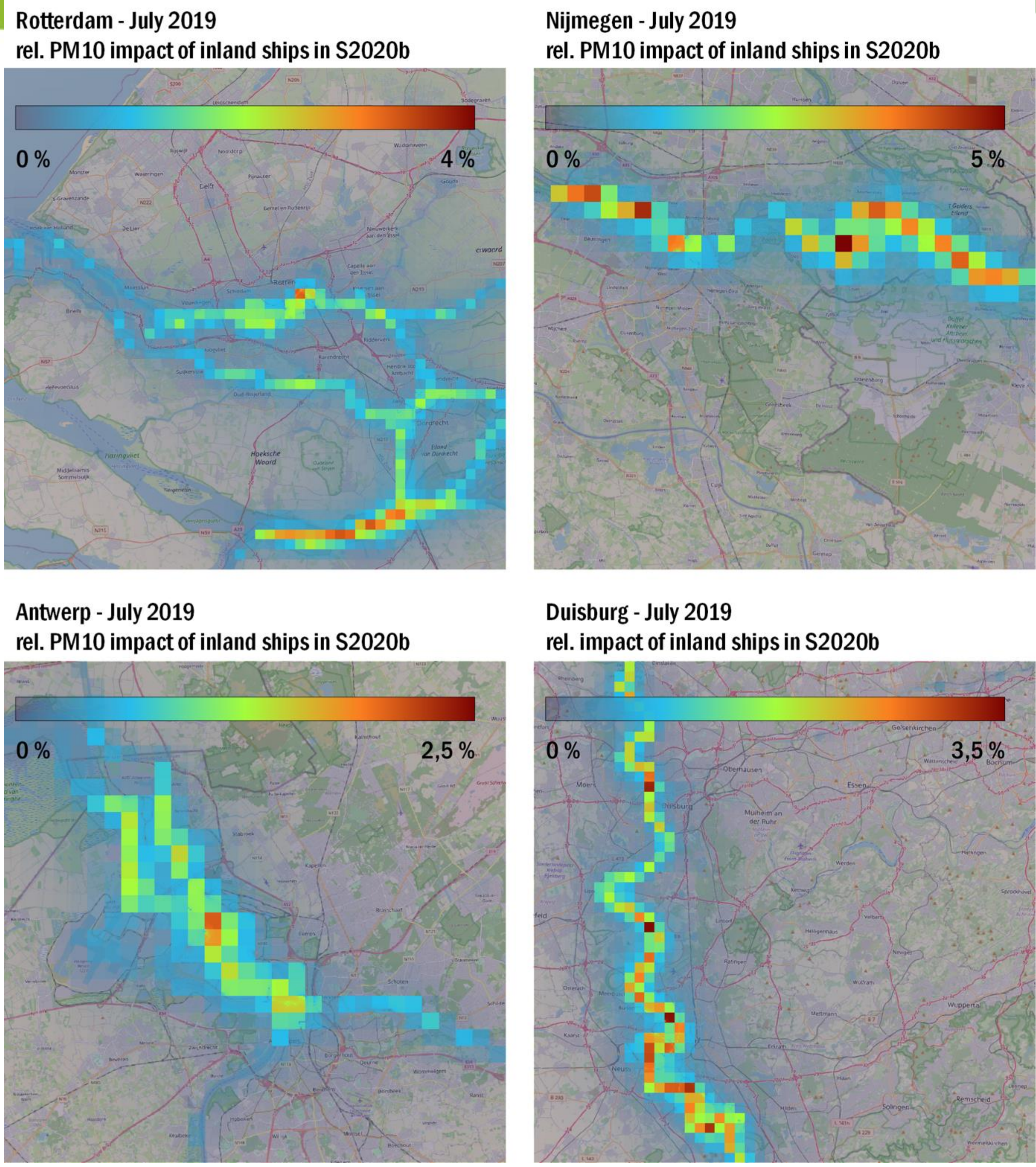


Figure 24: Relative impact of S2020b inland shipping PM_{10} emissions in July 2019.

Table 3: Monthly grid average concentrations of inland shipping impacts for all urban domains in S2020b as well es reduction potentials for the scenarios S2035b and S0235c compared to the S2020b scenario.

		monthly grid averages (or urban domain average) [µg/m³]											
		condition in base case				reduction potential compared to base case							
		S2020b				**S0235b**				**S2035c**			
pollutant	month	mean [µg/m³]	mean [%]	max [µg/m³]	max [%]	mean [µg/m³]	mean [%]	max [µg/m³]	max [%]	mean [µg/m³]	mean [%]	max [µg/m³]	max [%]
Rotterdam													
NO_2	January	0.57	2.9	4.81	22.4	-0.13	-0.7	-1.02	-4.8	-0.42	-2.1	-3.65	-17.0
NO_2	July	0.51	3.7	4.98	34.3	-0.14	-1.0	-1.23	-7.5	-0.36	-2.7	-3.59	-25.3
PM_{10}	January	0.03	0.3	0.27	2.0	-0.01	-0.1	-0.07	-0.5	-0.02	-0.2	-0.19	-1.4
PM_{10}	July	0.04	0.3	0.51	3.3	-0.01	-0.1	-0.14	-1.1	-0.03	-0.2	-0.39	-3.0
Nijmegen													
NO_2	January	0.97	5.9	9.74	45.0	-0.23	-1.4	-2.03	-9.4	-0.74	-4.5	-7.26	-33.5
NO_2	July	0.93	9.2	13.30	67.6	-0.22	-2.2	-2.26	-12.3	-0.69	-7.0	-9.05	-46.0
PM_{10}	January	0.04	0.3	0.49	3.7	-0.01	-0.1	-0.16	-1.2	-0.04	-0.3	-0.46	-3.5
PM_{10}	July	0.05	0.4	1.17	8.1	-0.02	-0.1	-0.39	-2.7	-0.05	-0.3	-1.10	-7.6
Antwerp													
NO_2	January	0.30	1.2	3.03	14.2	-0.07	-0.3	-0.65	-3.1	-0.21	-0.8	-2.35	-11.03
NO_2	July	0.22	1.0	1.99	12.1	-0.05	-0.2	-0.46	-2.7	-0.15	-0.7	-1.53	-8.21
PM_{10}	January	0.03	0.2	0.23	1.2	-0.01	-0.04	-0.06	-0.4	-0.02	-0.1	-0.16	-1.03
PM_{10}	July	0.03	0.2	0.42	2.1	-0.01	-0.05	-0.12	-0.6	-0.02	-0.1	-0.32	-1.58
Western Rhine-Ruhr area													
NO_2	January	0.34	1.7	4.42	19.5	-0.06	-0.3	-0.79	-3.4	-0.26	-1.3	-3.33	-14.55
NO_2	July	0.41	2.3	6.11	31.3	-0.09	-0.5	-1.31	-6.8	-0.31	-1.7	-4.71	-23.65
PM_{10}	January	0.02	0.1	0.37	2.1	-0.01	-0.03	-0.10	-0.6	-0.02	-0.1	-0.32	-1.82
PM_{10}	July	0.04	0.2	0.56	3.5	-0.01	-0.1	-0.16	-1.1	-0.03	-0.2	-0.49	-3.20

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